REV LTR

2

THE **BOEING** COMPANY

VERTOL DIVISION · MORTON, PENNSYLVANIA

CODE IDENT. NO. 77272

NUMBER D8-2424-1

TITLE AN INVESTIGATION OF ADVANCED FLIGHT CONTROLLERS FOR AEROSPACE VEHICLES

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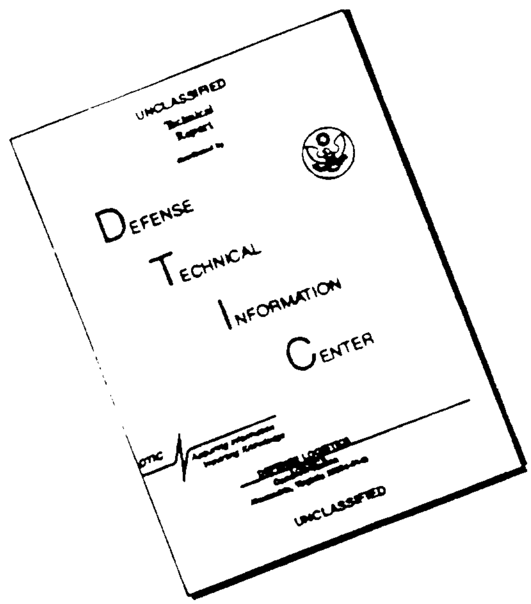

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ABSTRACT

This document summarizes results of objective studies to research, develop and evaluate concepts and state-of-the-art technology in the area of advanced flight controllers for aerospace vehicles. Studies were centered upon concepts which promised applicability to VTOL aircraft, with special attention devoted to sidearm controllers. The general conclusion is that evolutionary improvement to existing controller configurations promises greater overall acceptance and technological success than do revolutionary concepts. An extensive bibliography is provided in the Appendices.

KEY WORDS

Controls

Controllers

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1. INTRODUCTION

1.1 Objective

The objective of this study was to research, develop and evaluate concepts for improved flight controllers for aerospace vehicles, with special emphasis on velocity-stabilized VTOL aircraft. This document summarizes results of efforts in this area accomplished under 1967 and 1968 IR&D funding.

1.2 Background

Man's concern over the ease and accuracy with which he can perform manipulative tasks is at least as old as the histories of physiology and psychology themselves (References 1 through 6). It is not surprising to find that by the turn of the century man was rather deeply engrossed in identifying and measuring those parameters closely associated with his capability to perform manipulative functions (References 7, 8, 9 and 10). While controller efforts around 1900 had been restricted primarily to control of machinery (Reference 11) which evolved as part of the Industrial Revolution, the post-1900 era opened whole new areas of challenge in vehicular control. Before the flying-machine was ten years old, at least half a dozen methods had been proposed for improving the control devices. Even before the basic problems of aerodynamic stabilization and steering control had been solved satisfactorily, control designers were becoming concerned over the requirement to exercise simultaneous control over a multiplicity of parameters in both independent and coordinated modes. One of the first flight controller problems became that of providing simultaneous control over two operational parameters with a single control device. The selection of which two operational parameters should be controlled has been a matter of aviation history.

Since the beginning of powered flight, control systems and the control devices for coupling the operator to the flight control systems have centered about the power-attitude control concept. Whether this was an accidental evolution which has withstood the test of time because of its directness and simplicity, or whether it was a logically perfect and natural evolution which cannot be improved upon is of little importance to this study. The important fact is that through 60 years of being subjected to whatever challenges mankind has cared to impose, power-attitude flight control has emerged victorious as the primary mode of control for all powered aerospace vehicles. Consequently, one might expect that any system which proposes other than power-attitude control must have more convincing arguments than have been developed in the past if it is to be accepted or even considered. While flight control systems have remained relatively unchanged in concept, the same is not true of controllers. The mechanical control stick and control column have been the two major contenders for attitude control, but both suffer the major shortcomings of blocking the pilot's

ew of the instrument panel and of hampering ingress and egress. Directional controllers have remained consistently a coordinated combination of stick or yoke induced roll attitude and/or directional pedal control. Similarly, power control has centered about the control of power through throttles, collective handles or thrust levers, and the control of the rpm of something - prop, rotor, or turbine shaft.

As the number of discrete controls and manipulative functions increased along with increased operational capabilities and associated increased avionics complexity, it became necessary to reduce the pilots flight control burden by delegating flight control tasks to automated pilot-assist functions. The autopilots of the 1930's provided for nothing more than stabilization of the aircraft about some set of steady state flight parameters. To change this state, the pilot had to revert to the conventional control system, establish a new state, and command the autopilot to maintain the new state. In a further attempt to simplify this task, continuously variable controls were added to the autopilot, so that reversion to the primary mode was not required to effect changes. By manipulating the autopilot functions, the pilot could couple manually limited guidance functions with the flight control functions. Later innovations directly coupled automatically generated guidance information into the autopilot for automatic flight control during some phases of the mission profile. But always the lot had the option of assuming manual control of or reversion the primary power-attitude flight control system. Consequently one concludes that even though conventional sticks, columns and foot pedals have some shortcomings, they have been maintained for primary control. In other than the primary mode, those flight control functions which may be automated for pilot relief during particular phases of flight must be under his command. Additionally, even though an automated or assist mode is provided, the pilot must be able to revert to direct primary manual control of the vehicle, either with degradation in performance and increased task loading, or with provisions for improved control of continuously variable parameters for which pilot relief was not provided.

In early 1960 MIT convinced AVLABS that there were advanced flight control concepts (AFCC) which merited consideration as a replacement for power-attitude flight control (PAFC). A subsequent program at MIT demonstrated the feasibility of AFCC in some portions of the NCH-46 flight envelope and AVLABS decided to pursue development. The arguments associated with a comparison of AFCC and PAFC are inappropriate here, for it is obvious that each new flight control system, regardless of whether AFCC or PAFC, will offer advantages over the existing flight control systems in whatever class of vehicle is being considered. It is equally obvious that the present controller concepts will be at least as unsatisfactory for future flight control systems as they are for present systems.

Perhaps it is appropriate at this point to examine the improvements desired in advanced flight control systems. Once these have been defined, it then becomes easier to describe and evaluate new concepts for coupling the operator to these systems.

1.3 Flight Control Systems

The flight control system is perhaps the system most subject to pilot factors, and one of the many which impose limitations on the effectiveness of aircraft operations. Through the years much effort has been expended in identifying and understanding inherent helicopter flight control parameters and in determining values which will provide the best control system characteristics for VTOL aircraft. Considerable effort also has been expended in investigating the human factors involved in VTOL aircraft control. Unfortunately, too often the pilot has been placed outside the control loop, or at most, been considered the end point of an open loop control system. At this point, it should be understood that in all manned aircraft, the pilot is at all times responsible for the control of the aircraft. Responsibility for control implies, by the definition of control:

A. Regulating the aircraft and its systems to keep them within safe operating limits.

B. Directing the aircraft performance to assure successful accomplishment of assigned mission responsibilities.

C. In cases of conflicting requirements which make mandatory the ordering of Items A and B above, decision making to determine which shall be sacrificed, mission effectiveness or safety.

If a pilot is assigned mission and control responsibilities, he must be provided also with the command authority necessary to effect control until such time as he is relieved of his responsibilities. It should be realized that no avionics system devisable can relieve a pilot of man-assigned responsibilities; it can only be designed to assist the pilot in exercising his command authority in the fulfillment of these responsibilities.

Paraphrasing all of this into simple words which an avionics design engineer might grasp more easily, any avionics device designed to assist a pilot in exercising his command authority must:

A. Operate only when commanded to do so by the pilot.

B. When operating, do the job better than the pilot can by some standard of "betterness", such as speed, accuracy, etc.

C. When not operating, must not degrade the pilot's ability to do the job himself.

...veral research programs have been sponsored by both government and industry for the definition of a practical, advanced flight control system which will provide "optimum" control-characteristics for VTOL aircraft. If the general mandatory considerations outlined above for command/control are complemented with measures to satisfy safety, comfort and performance requirements, a set of guidelines can be devised for the design of VTOL control systems. These latter requirements are listed in greater detail as follows:

A. Safety

(1) Must automatically maintain aircraft control parameters within the established aircraft stress and control recoverability limits when under automatic operation and must accept pilot limitations when under non-automatic operation.

(2) Must provide automatically those control functions necessary to relieve the pilot of physical and psychological fatigue burdens to the maximum extent possible.

B. Command

(1) Must give the pilot the choice of automatic or manual control of the system.

(2) Must accept both direct and corrective commands from the pilot when operating in the automatic mode.

(3) Must return complete flight control authority to the pilot in the failure/manual mode.

C. Performance

(1) Must automatically sense, analyze and react to aircraft and control system parameters to maintain maximum performance for a selected set of operating conditions.

(2) Must have optimized display and controls to reduce scanning, facilitate data interpretation, resolve natural/synthetic cueing ambiguities, facilitate decision making, and simplify control action in both the automatic and non-automatic modes.

(3) Must accept inputs from available automatic navigation, weather avoidance, terrain avoidance, and other flight safety and comfort devices.

D. Cost/Effectiveness

(1) Must be as inexpensive, light, small, adaptable, maintainable, reliable, efficient, survivable, available, safe, and simple as possible, consistent with the requirements above.

Most of these requirements are interrelated in such a manner that a change in the methods for satisfying one requirement often will affect other requirements. For example, if ease of operation is effected to reduce physical fatigue, it is also possible that safety may be increased and training requirements may be reduced. However, it is perhaps easiest to consider each requirement on its individual merit to see how controller requirements might be affected. After all requirements have been defined for the controller, one then may interrelate and trade-study these requirements from the system standpoint.

1.4 Safety

First, let us look at the safety aspects in greater detail. An expressed desire for increased safety in any system implies an existing deficiency in the safety area or the potential for accidental loss of life or material. To determine where advanced controller concepts might best contribute to increased safety, a study was made of the relationship of pilot factors to Army rotary wing aircraft accidents. The results of this study were reported in detail (Reference 12), but the more important facts are repeated here.

1) For operation in USARVN, accidental loss of aircraft and accidental aircraft fatalities outnumber combat aircraft losses and combat aircraft fatalities by about 2:1.

2) Repair and/or replacement of aircraft accidentally damaged in RVN operations is costing the U.S. Army in excess of $5,000,000 per month.

3) RVN operations involve more than 100,000 helicopter flying hours per month with associated accident rates of about 3×10^{-4} per flight hour (30 per month).

4) Pilot factors are involved in 79% of all accidental damage or losses in RVN operations.

5) The four major helicopter pilot factors are:

a)	Loss of rpm, high gross weight, high density altitude	15%
b)	Improper use of flight controls	15%

c) Misjudgment of altitude, distance or position 15%

d) Failure to see aircraft or object in time to avoid collision. 14%

Review of 19 major CH-47 accidents (Reference 13) reveals results somewhat similar to those expressed in paragraph (5) above, i.e.:

a) Loss of rpm, high gross weight, high density altitude 28%

b) Pilot not IFR qualified 17%

c) No ground reference 11%

d) Taxi maneuvering 11%

e) Failure to see object in time to avoid collision (or near miss) 17%

f) Improper use of flight controls 5%

Perhaps it is worthwhile at this point to draw several conclusions from these two reports:

1) Since accidental losses outnumber combat losses by about 2:1, it would appear that a 50% reduction in accidents might represent as great a savings as a 100% reduction in combat vulnerability. Certainly the former would be easier to realize.

2) Loss of rpm, high gross weight, high density altitudes, misjudgment of altitude, misjudgment of position, misjudgment of distance, and failure to see obstacles all pertain to information which the pilot requires and does not have available in the cockpit. This deficiency is associated with 44% of the pilot factors. Improper use of flight controls accounts for 5 to 15% of the pilot factors. It would appear then that a 33% improvement in sensors and displays might represent as great a savings as a 100% improvement in flight controls, and again the former seems more achievable.

3) It is possible that twelve of the nineteen CH-47 major accidents might have been avoided with the addition of performance, navigation and collision avoidance equipment and displays. Only two of the nineteen might have been avoided with improved controls.

In view of these conclusions, studies were made of twelve advanced flight control configurations which showed potential for reducing accidents. Pilots and engineers were questioned to assess their feelings regarding the potential of each configuration in this respect. A computer program was used to analyze the answers to the questionnaires, with the following results:

a) The addition of an improved control system to the basic CH-47 might reduce accidents by as much as 11%.

b) The addition of improved displays to the basic CH-47 might reduce accidents by as much as 16%.

c) The addition of improved control and display systems into an advanced integrated cockpit might reduce accidents by as much as 32%.

The purpose of introducing these conclusions has not been to argue the importance of either controllers or displays, but merely to pave the way for comments and reactions which will be reported later concerning the relative merits of improved displays versus improved controllers.

PRELIMINARY CONCEPTS

2.1 AVLABS Preliminary Concept

AVLABS initial concept for an advanced flight controller for the Tactical Aircraft Guidance System (TAGS) is best described in the early TAGS briefings given by AVLABS in an attempt to arouse technical and financial interest in the TAGS development. "A description of the TAGS four-axis controller illustrates the instinctive simplicity of the flight control concept. The controller resembles a 'T'-handle, mounted at a 45 degree slant rearward (towards the pilot) with the pilot's grip being at the top of the 'T'. Visualize a small model of the aircraft as the pilots grip, where movement of the model produces a corresponding movement of the actual aircraft, i.e., straight fore and aft translational movement commands a change in speed in the chosen direction proportional to displacement, which is ground referenced in hover and air mass referenced in cruise flight; straight right or left translational movement commands transverse speed proportional to displacement which is ground referenced in hover and air mass referenced in cruise flight (used in cruise flight only to command intentional sideslip); right or left angular rotation of the pilot's grip (bank and turn of the aircraft model) commands a turn whose rate of change is proportional to deflection (yawing velocity in hover, coordinated turn in cruise); angular rotation of the pilot's grip upward and downwards (raising or lowering of the nose of the model) commands rate of change of altitude with full upward rotation commanding rate of pitch change for maneuvers such as the loop. Any combination of these commands may be mixed and all modes blend automatically between hover and cruise flight without requiring pilot action or selection". This word description is indicative of two things; (1) the degree of detail with which AVLABS have visualized the operational requirements of their controller, and (2) recognition by AVLABS that there are maneuvers in which pitch control will be more important than vertical velocity control. Using this word concept as a basis, LTC R. E. Richter, who is an employee of Garrett Corporation, produced the configuration drawing shown in Figure 1. Note the dead-man's switch and feel-adjust knobs. Subsequently, this concept was advertised so strongly that it soon became synonymous with TAGS. In fact, the only printed public disclosure of TAGS to date - which appeared in Aviation Week and Space Technology on 25 March 1968 - describes TAGS as follows:

> "Single control lever system for helicopters is being studied by the Army under the designation of TAGS, for Tactical Aircraft Guidance System. The single lever control would replace conventional collective and cyclic control levers".

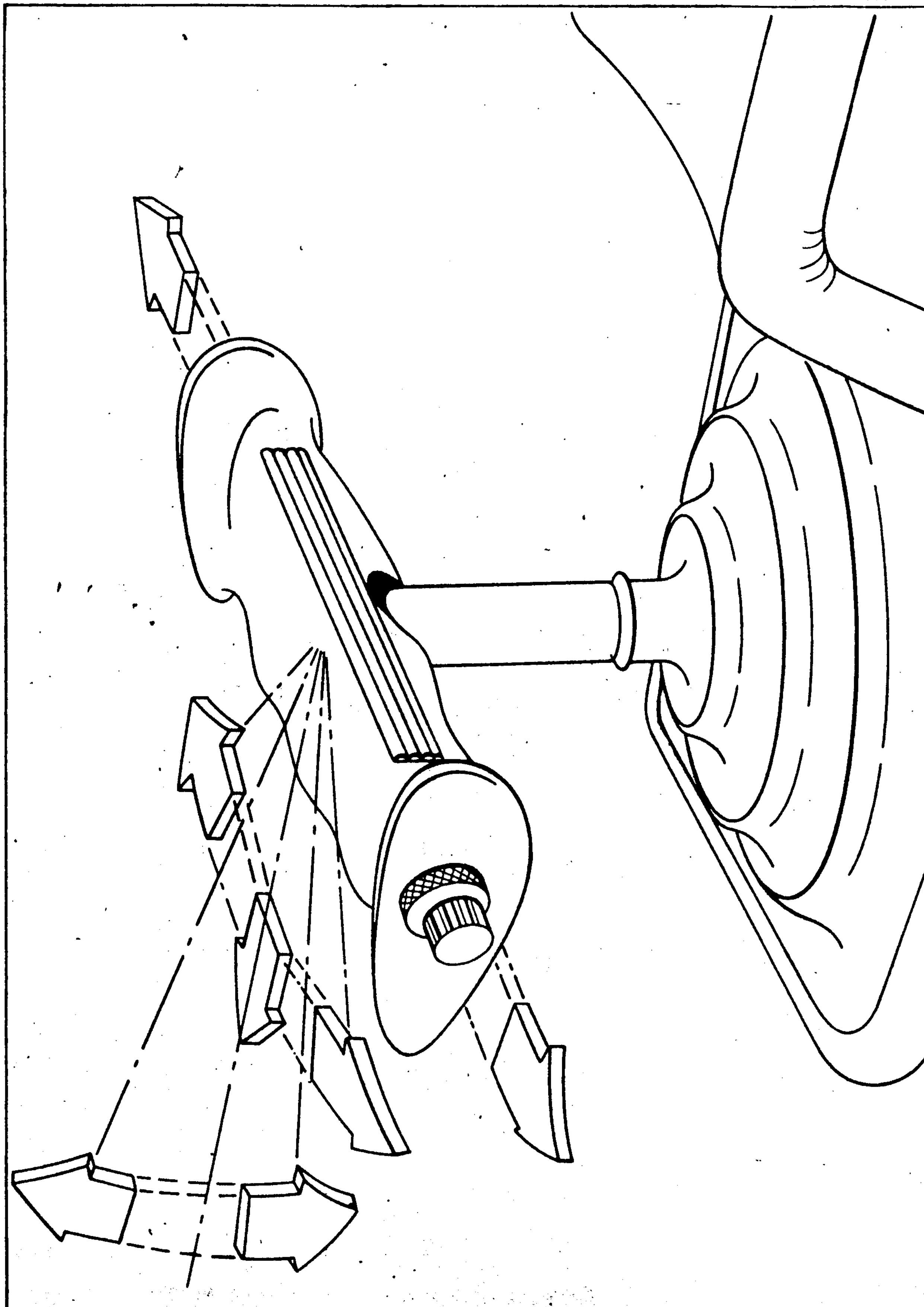


Figure 1. Conceptual Sketch of AAVLABS Preliminary Side-Arm Controller.

No further description of TAGS was given. The conclusion is that AVLABS has a definite idea about what controller hardware for TAGS should be.

AVLABS immediately set about to build a model of their concept according to the sketch shown in Figure 2. This model is best described by U.S. Army Aviation Materiel Laboratories (Fort Eustis, Virginia) Code 81996 Drawings Numbered 20067120 through 20067202. Because of the limited shop capabilities to machine and fabricate such a device at AVLABS, the first model was understandably crude. The model had been designed specifically to make use of off-the-shelf components. No parts specifications were developed, and the Bjourns high reliability precision 10-K potentiometers intended for use became difficult to obtain. Consequently, only one model was built as a laboratory experimental device. Even so, AVLABS had hoped that the model could be used for determining controller dynamic characteristics both in the simulator and the NCH-46 at M.I.T. Two problems, that of zero-detent (centered) output and that of redundancy of channels were identified immediately. AVLABS felt that the controller should have zero electrical output when the controller was positioned to command zero velocity. The redundancy problem was circumvented by making some channels triply and some quadruply redundant.

2.2 M.I.T. Preliminary Concept

M.I.T., meanwhile, was more interested in exploring the AFCC than it was in controller development. In addition, it did not want to hold up its feasibility program while waiting for controller development. In view of its limited budget, M.I.T. used available hardware to fabricate two two-axis side-arm controllers, of the type illustrated in Figure 3. Each axis was connected to a single linear potentiometer pick-off to produce the signals shown in the diagram. The twist-lock friction knobs at the end of each controller served the same purpose as the dead man's switch shown in the AVLABS concept, that is to lock all axes simultaneously at the selected values. One set of these controllers was installed in the M.I.T. fixed base simulator. Another set was added to the pilot's position of the NCH-46 in addition to (rather than in lieu of) conventional controllers. The simulator controllers were operated by Vertol engineers and test pilots. The most general comments were that the controllers were extremely sensitive. The problems of sensitivity did not appear unsurmountable, and M.I.T. was the first to admit that improved controllers were desirable. The conclusion is that M.I.T. is not entirely satisfied with the original two-axis dual side-arm configuration, but is not making any special effort to optimize this controller configuration, although it is trying to improve it.

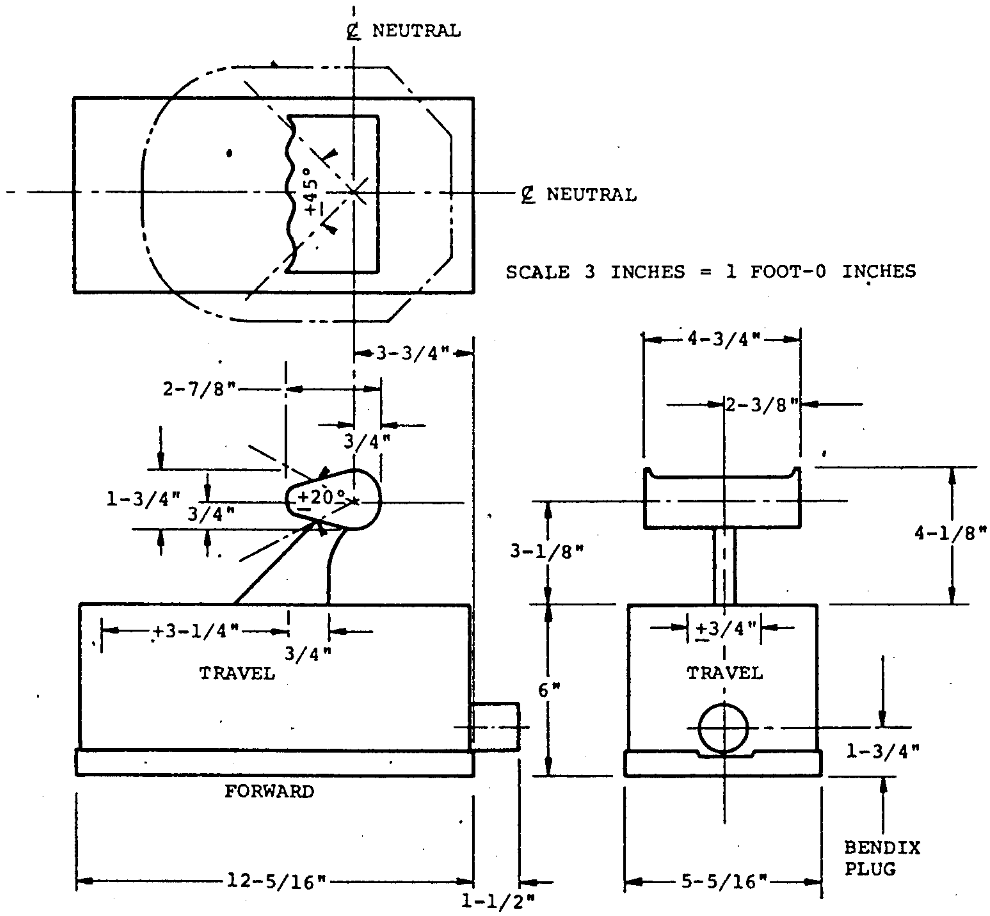
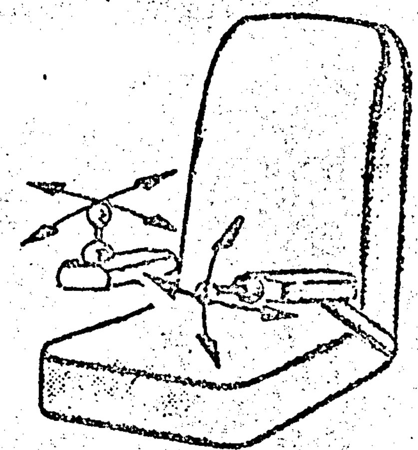


Figure 2. Four-Axis Pilot Controller - O.A. Dimensional SK.



RIGHT HAND

Fore & Aft: Longitudinal Control
Side To Side: Lateral Control

LEFT HAND

Up & Down: Vertical Control
Side To Side: Directional Control

FIGURE 3

AN ADVANCED FLIGHT CONTROL SYSTEM
FOR ARMY AIRCRAFT

2.3 Vertol Preliminary Investigation

Upon initial exposure to and discussion of the AVLABS controller concept at AVLABS, the general concept seemed acceptable. AVLABS, in explaining the concept, pointed strongly to the fact that they were not interested in funding or developing controllers which involved control stick, control column or foot pedal concepts. In the initial TAGS presentations by AVLABS, the following HUMMRO statement had been quoted:

> "Ideally, the Army aviation pilot training program should consist of a three-week transition course for jeep, truck, and tank drivers" (Reference 14).

When it was suggested that a set of automobile type controls in a helicopter might offer the simplest means for such a transition, the suggestion was not received with enthusiasm by AVLABS. TAGS managers at AVLABS pointed out a requirement that the controller should be equally applicable to right or left handed persons, and further indicated their intent to have two or three prototypes built with which to experiment. This indicated that not only had a concept been formulated firmly, but also that at least one method of mechanization had been conceived. Assuming that the concept was feasible from both the operational and mechanization standpoints, Vertol began seeking the best source for such a controller for use in a demonstration program.

Conferences between Vertol engineering personnel in June 1967 brought to light the following questions:

(1) Should pilot's and copilot's controller follow one another in a dual installation?

(2) Is a dead-man's switch necessary?

(3) Should there be a zero-detent?

(4) What is the best mechanization scheme?

(5) What are the reliabilities associated with each of the components which may be associated with such controllers?

(6) What are the feel requirements?

(7) What are the dead-zone limitations?

Further checking within Vertol resulted in the identification of Measurement Systems Incorporated (MSI) as the most likely source of knowledge on such devices. Subsequent contact with the Human Engineering Division, Maintenance Design Branch, Wright Patterson Air Force Base, Dayton, Ohio revealed that they knew of no four-axis controllers in existence. As a result of their having built

ir own two- and three-axis models for experimental purposes, y cautioned against problems of inadvertent cross coupling, especially during maneuvers. All of their models had required very heavy spring damping to alleviate this problem and they recommend contacting MSI and the USAF Aeromedical Research Division. This division claimed to have many drawings for proposed controllers, but none for four-axis control. The Flight Dynamics Laboratory knew of no continuing three-axis or four-axis controller development programs because of the large physiological problems encountered in human wrist articulation. They suggested that anthropological requirements be given much attention in the development of controller concepts and that we discuss this with the Anthropology Group at WPAFB.

Faced with the requirement for price and delivery schedule information for estimating purposes, the next logical step was to contact every potential vendor source which could be identified. To this end, 26 companies were contacted, but only eight produced evidence of any experience in the controller field. This experience is outlined in Table I, along with general comments pertinent to advanced multi-axis controller development.

Using the existing AVLABS drawing and description as guidelines, Vertol artists and designers produced the conceptual sketch of a four-axis single side-arm controller shown in Figure 4. Concurrently, a preliminary general description of the controller (Appen- A) was generated to facilitate discussion of controller development with potential vendors. Subsequently, representatives of the companies listed in Table I were invited to Vertol for a technical briefing on the concept. Each was encouraged to assess his company's interest and, if so inclined, to submit an unsolicited proposal for the production of demonstration models. Proposals from The Bendix Corporation and Measurement Systems, Incorporated (the only respondents) were reviewed. Only the Bendix configuration bore physical resemblance to either the AVLABS or the Vertol concept. Based on the prices quoted for specific quantities, the cost/learning curve of Figure 5 was extrapolated. The estimated costs shown are for limited production quantities, and are exclusive of research and development costs which were anticipated to be in the neighborhood of $100K - $150K. The costed controllers, which could be available approximately nine months after receipt of a definitive procurement specification, would be flight safety qualified only, with additional time and costs required for full military qualification.

Considering the inadvisability of saddling an advanced flight control system development with a specific controller concept of questionable feasibility, division management directed that as many concepts as practicable be examined for the purpose of determining the most promising two or three concepts. These two or three concepts then could be developed and evaluated with respect to the advanced flight control systems into which they would be incorpted. At this point it was realized that the development of an advanced controller concept would be both costly and time-consuming.

VENDOR SOURCE	EXPERIENCE	COMMENTS
NAVIGATION & CONTROL DIVISION THE BENDIX CORPORATION TETERBORO, NEW JERSEY 07608	1. AUTOPILOTS FOR THE A4D AND THE F4H. 2. FORCE TRANSDUCERS FOR THE P-3A AND THE C-141. 3. AUTOSYN, MICROSWITCH AND STRAIN GAGE CONTROLLERS.	NONE
DEFENSE ELECTRONICS DIVISION GENERAL ELECTRIC COMPANY BINGHAMTON, NEW YORK 13902	1. HAVE BUILT 2-AXIS FORCE CONTROLLERS IN STANDARD B-8 GRIP. 2. USE SEMICONDUCTOR STRAIN GAGES ON CANTILEVER BEAM - ELECTRICAL OUTPUT DIRECTLY PROPORTIONAL TO APPLIED FORCE - MAXIMUM OUTPUT 5VDC - TEMPERATURE STABLE - ULTIMATE LOAD 300 POUNDS. 3. HAVE WORKED WITH 1, 2, AND 3 LEVELS OF REDUNDANCY. 4. CONTROLLER FOR 666A PROGRAM HAS ACCUMULATED 1000 LABORATORY AND 25 FLIGHT HOURS WITHOUT FAILURE. IT REQUIRED 1½ YEARS UNDER GE FUNDING AND ½ YEAR UNDER GOVERNMENT FUNDING TO DEVELOP. 5. HAVE BUILT REDUNDANT COLUMN AND WHEEL (SPEC. MEMO 67-2610). 6. HAVE BUILT IN-GRIP STICK TRANSDUCERS (DATA SHEET A422). 7. HAVE BUILT F-4 MOTION TRANSDUCER (DATA SHEET A404).	1. A 4-AXIS CONTROLLER PROBABLY WOULD REQUIRE MORE THAN 2 YEARS TO DEVELOP. 2. CONTROLLERS RUN ABOUT $12.5 PER AXIS IN PROTOTYPE AND ABOUT $3K PER AXIS IN PRODUCTION. 3. SENSORS SHOULD BE KEPT OUT OF GRIP TO REDUCE VIBRATION OF ELECTRONIC COMPONENTS. 4. MORE INTERESTED IN SYSTEM DESIGN THAN IN HARDWARE RESPONSIBILITIES.
MILITARY PRODUCTS DIVISION HONEYWELL, INCORPORATED MINNEAPOLIS, MINNESOTA 55408	1. HAVE WORKED MOSTLY ON SPACE CONTROLLERS, INCLUDING 3-AXIS LEM WHICH COST $21K EACH 2. HAVE WORKED ON 4-AXIS TRANSLATIONAL CONTROLLERS WHICH WOULD COST $25K EACH. 3. HAVE MANY 2-AXIS QUADRUPLEX CONTROLLERS IN OPERATIONAL AIRCRAFT, SUCH AS THE ONE IN AAFSS WHICH COST $4K IN PRODUCTION, AND THE ONE IN THE C-5A. 4. IN PRODUCTION FOR 3-AXIS CONTROLLER FOR APOLLO - IT USES LVDT'S.	1. DEVELOPMENT COSTS FOR A 4-AXIS CONTROLLER WOULD BE IN EXCESS OF $100K. 2. DEVELOPMENT TIME FOR A 4-AXIS CONTROLLER WOULD BE 8 MONTHS TO PROTOTYPE AND 16 MONTHS TO DELIVERY OF FIRST QUALIFIED UNIT.
AEROSPACE GROUP HUGHES AIRCRAFT COMPANY CULVER CITY,CALIFORNIA 90232	1. HAVE BUILT SEVERAL EXPERIMENTAL 3-AXIS AND 4-AXIS CONTROLLERS. 2. HAVE BUILT 4-AXIS CONTROLLER WITH 3-AXIS BALL AND SIDE BUTTON UP-DOWN. 3. HAVE BUILT 3-AXIS PISTOL GRIP CONTROLLER FOR PITCH, ROLL, AND YAW. 4. HAVE BUILT 3-AXIS PALMAR CONTROLLER WITH INTERNAL STRAIN GAGES. 5. ALL CONTROLLERS ARE EXPERIMENTAL - HAVE NOTHING OFF-THE-SHELF. 6. HAVE DUAL SIDE-ARM JET TRANSPORT CONTROLLERS IN FLIGHT TEST AT WPAFB. 7. ARE WORKING ON MOCK-UP, SIMULATION AND PILOTS' EVALUATIONS FOR BOTH FIXED-WING AND SPACE APPLICATION FOR SAC AND NASA, RESPECTIVELY. 8. ARE CONSIDERING 4-AXIS CONTROLLER FOR SPACE APPLICATION ONLY.	1. USE OF DRY FRICTION HURTS BREAKOUT AND STICTION. 2. RECOMMEND USE OF VISCUOUS DAMPING. 3. RECOMMEND CONSIDERATION OF 4-AXIS WHEEL OR 4-AXIS T-BAR.
ASTRONICS DIVISION LEAR SIEGLER, INCORPORATED SANTA MONICA, CALIFORNIA 90406	1. UNDER CONTRACT TO THE AF FOR A 5-AXIS CONTROLLER FOR THE HUGHES 300. 2. ARE BUILDING A CONTROLLER FOR THE ZERO-ZERO VERSION OF THE CH-3C. 3. HAVE PROPOSAL TO LOCKHEED AND THE USAF FOR SINGLE SIDE ARM CONTROLLER FOR THE F-104B. 4. HAVE PROPOSAL TO FAA FOR SINGLE SIDE ARM CONTROLLER FOR THE SST.	

VENDOR SOURCE	EXPERIENCE	COMMENTS
MISSILES & AEROSPACE DIVISION LTV AEROSPACE CORPORATION DALLAS, TEXAS 75222	1. HAVE EXPERIMENTED WITH MANY CONTROLLERS, INCLUDING A STUDY OF FORCE TRANSDUCERS FOR THE XC-142. 2. HAVE BUILT WAIST-MOUNTED CONTROLS FOR SPACE BELTS. 3. CONCEIVED CONTROLLER FOR DYNA SOAR. 4. DEVELOPED AND QUALIFIED SIDE ARM CONTROLLERS FOR GEMINI IX ASTRONAUT MANEUVERING UNIT (AMU) 5. NASA SHARED SPACE CONTROL AND GRAPPLING ANCHORING MANIPULATOR PRESENTLY UNDER TEST ON HYDRAZENE MODEL FRICTIONLESS PLATFORM.	
MEASUREMENT SYSTEMS, INC. NORWALK, CONNECTICUT 06850	1. HAVE MANY 2-AXIS AND 3-AXIS FORCE CONTROLLERS AVAILABLE FOR CATALOG DELIVERY IN 90-120 DAYS. 2. HAVE EXPERIMENTED WITH 6-AXIS SUBMARINE CONTROLLER. 3. MAKE CONTROLLERS FOR GE FIRE CONTROL TURRET ON AAFSS. 4. MAKE 2-AXIS X-Y ISOTONIC CONTROLLER USING POTENTIOMETERS (MODEL 525). 5. MAKE 3-AXIS ISOMETRIC CONTROLLER (MODEL 437). 6. MAKE NO 4-AXIS CONTROLLERS.	1. 3-AXIS IS UPPER LIMIT OF DISPLACEMENT CONTROLLER FOR ADEQUATE RESOLUTION AND REASONABLE SIZE. 2. INTERESTED IN BITS AND PIECES AND CANNOT SUPPORT A LARGE R & D PROGRAM.
SPERRY PHOENIX COMPANY SPERRY RAND CORPORATION PHOENIX, ARIZONA	1. HAVE PROPOSED, DEVELOPED AND MANUFACTURED SIDE STICK CONTROLLERS, INCLUDING 3-AXIS CONTROLLER FOR MOL, 2-AXIS GRIP FOR THE A-6A, AND A 2-AXIS VARIABLE CHARACTERISTIC CONTROLLER. 2. HAVE NEVER MADE A 4-AXIS CONTROLLER. 3. PROPOSED A QUADRUPLEX CONTROLLER FOR VERTOL'S FLY-BY-WIRE.	1. ARE NOT IN THE CONTROLLER BUSINESS.

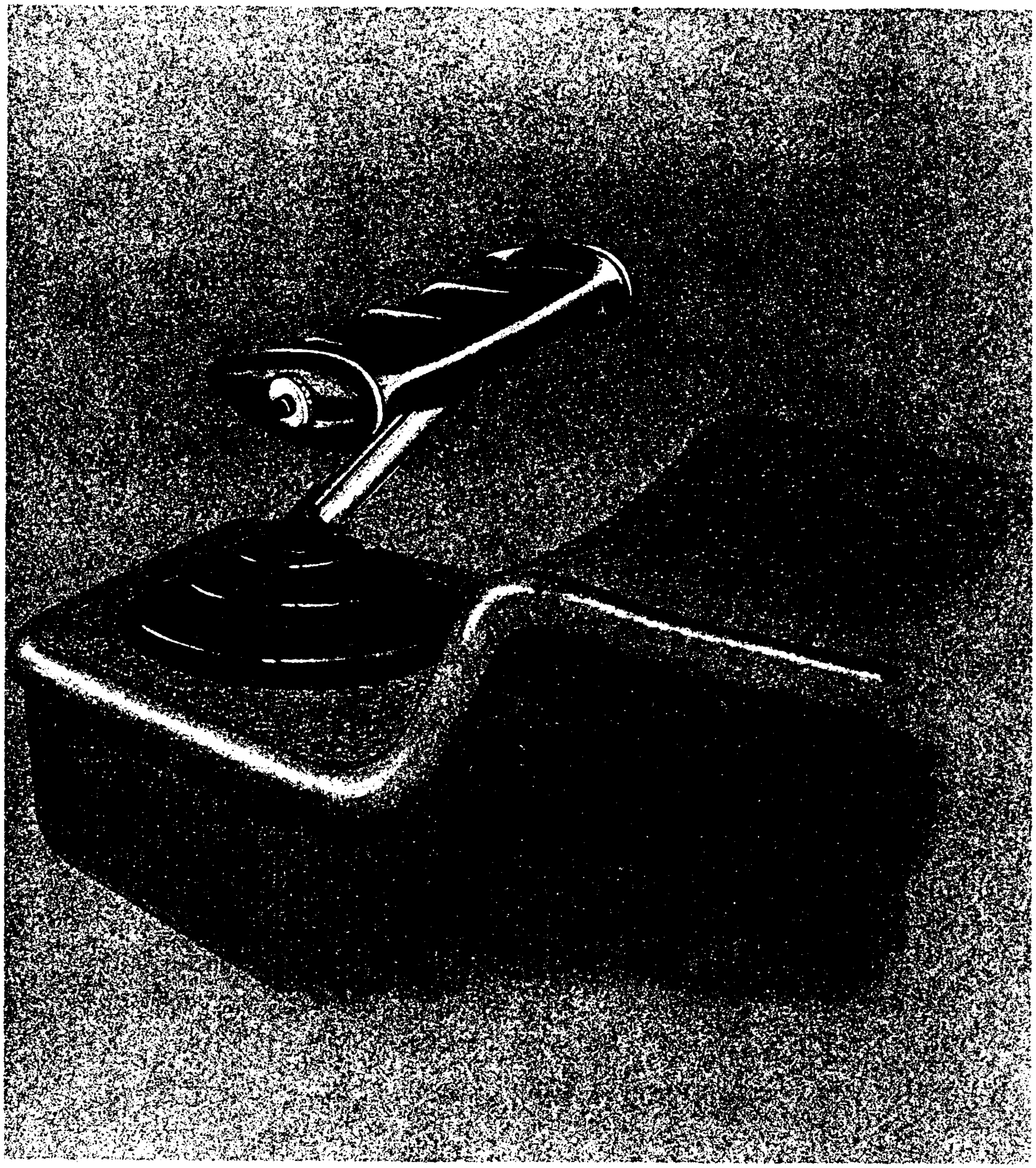


Figure 4. Vertol Artist's Concept of Side-Arm Control.

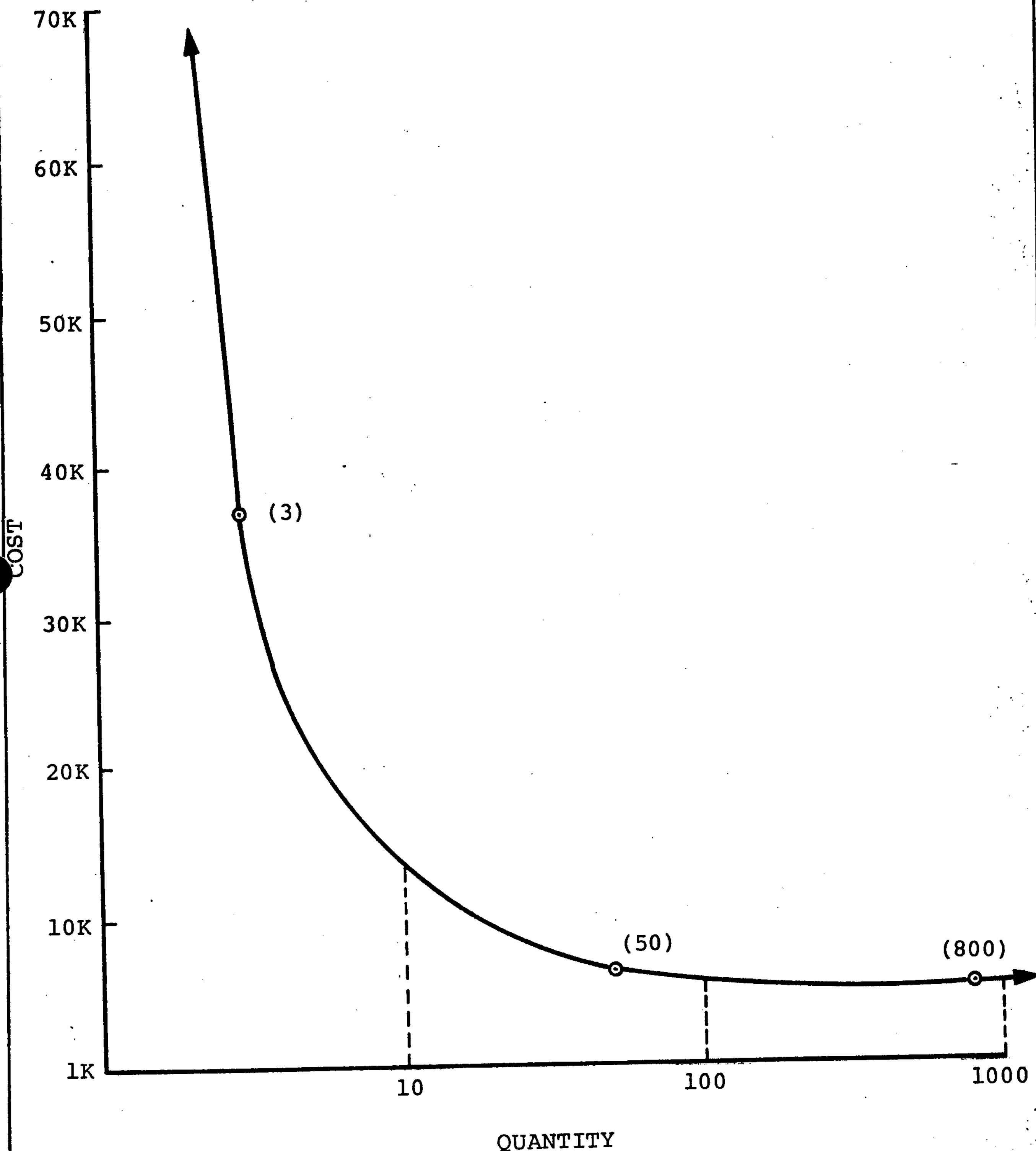


Figure 5. Four-Axis Side Arm Controller - Cost Versus Quantity.

In order to meet time schedule interfaces with near-term flight control development programs, it was suggested that one approach might include electrification of existing controls. This approach was a reasonable one in view of the fact that in all probability the foot pedals would have to be maintained in all advanced concepts for the purpose of providing toe brakes. However, this approach had several inherent problems as applied to a dual place aircraft. While the controls would be mechanically separate, they would have to be physically identical with respect to force feel, stiffness, damping, displacement, magnetic braking and inertia. This would be particularly true of demonstration installations where one controller was electrical and the other was to remain mechanical for backup or safety-of-flight purposes. Additionally, such a system would require incorporation of techniques whereby the electrified controller would drive the mechanical controller to positions comparable to those of the electrified controller. As an alternative approach, it was suggested that the side arm controllers used in the AH-1G and the CH-54 be examined with regard to their applicability to advanced flight control system development. These configurations are described in detail in appropriate References 15, 16.

Generally, the AH-1G installation consists of conventional controls in the aft (pilot's) cockpit and side arm controls in the forward (gunner's) cockpit. The forward controls consist of a 2-axis right side arm cyclic controller, a single axis left side arm collective controller and directional pedals. All controllers are connected mechanically in parallel with the pilot's controls. The controllers are an outgrowth of the early side arm controllers on the Bell Scout. Apparently, the most serious drawback is the decreased leverage which can be exerted due to the shortened moment arms of the hand controllers.

The CH-54A installation consists of conventional controls at both the pilot's and copilots positions plus side arm controls at the aft-facing pilots position. The aft-facing pilot's station is provided with a single-axis left side-arm collective pitch stick which incorporates hoist, flood light, coupler release, and barometric altitude release switches in its grip. The hover control stick is a 3-axis right side-arm controller which closely resembles the standard B-8 grip. Stick release, trim release, ICS-RADIO and cargo switches are incorporated. The hover stick is electrically actuated and provides the aft-facing pilot a means for accurately maneuvering the vehicle in pitch, roll and yaw attitudes during load handling operations. The aft-facing control may be released from either the pilot's or the copilot's position. The hover stick has three modes of operation which dictate various combinations of the stick, the coupler, the AFCS amplifier and the AFCS servo valves. The hover stick has ±10% authority, which may be extended with stick beep trim.

ther of these configurations was satisfactory because the AH-1G trollers were mechanical and the CH-54 controllers were limited authority and not intended for a primary means of control over the entire operating regime of the vehicle.

Attempts to procure a LEM or Apollo Block II controller failed because delivery of production models was not anticipated until late 1968 and the development of an engineering model might have taken longer. In addition, the one LEM controller then in the possession of Honeywell was the property of Grumman Aircraft Engineering Corporation and was so committed to existing space programs as to be unavailable for out-of-house programs.

By September 1967 it was clearly indicated that the most logical solution to the problem of advanced controller development for TAGS was to devise an in-house developmental program which would lead to a flight safety qualified controller in a meaningful time frame. Such a program was included as part of the TAGS proposal (Reference 17). The general contents of this portion of the proposal are included as Appendix II. Because there has been relatively little experimental effort in the field of four-axis side-arm controllers, this element of the TAGS was considered to be an item of significant risk. Considering the time schedules, the degree of developmental risk involved and the associated cost of development, Boeing-Vertol suggested the alternative approach t conventional, off-the-shelf controls, components and sensors considered for use in synthesizing both experimental and developmental systems. It specifically was suggested that input signals might be provided by Linear Variable Differential Transformers (LVDTs) coupled to conventional controls. Not only would this approach reduce developmental costs and allow more time for optimal controller development, but also might preclude any confusion in the minds of flight test personnel as to which subjective advantages/disadvantages are attributable to the introduction of advanced controller hardware and which are attributable to the introduction of advanced flight control concepts.

For the purpose of in-house development of advanced flight controllers, the decision was made to follow sound system engineering procedures (Reference 18) to the maximum extent possible. Since no official SOR/OSR/ADO existed for an advanced controller, it was necessary for Vertol to consider all the information presented heretofore and to develop its own specific qualitative operational requirements for an advanced controller.

One of the most probable reasons of the non-existence of an SOR/OSR/ADO was that inadequate research and development had been completed to:

1) Specify the operational requirements
2) Assess the military value
3) Assess the technical feasibility
4) Assess the economic feasibility

However, a reasonable judgement had been made which concluded that advanced control concepts were desirable to meet the objectives stated in Appendix II. From the foregoing judgements and conversations with potential using agencies (which will be described later) it was apparent that the nature of an advanced controller development would be closer to a specified ADO than to an SOR/OSR. In November 1967, Vertol developed the following general development objective for an advanced controller.

> "Provide the optimum method for coupling human (operator) transducers (motor processes) to an advanced flight control system for the purpose of controlling a vehicle's functional flight parameters with respect to a specific coordinate reference system."

To describe development objectives within the intent of AFSCM 375-5, it was necessary to investigate in greater detail the following areas:

1) Statement of background and reasons for required operational capability

2) Logistics Concepts

    a) deployment, location and dispersal
    b) manpower requirements
    c) facilities requirements
    d) material requirements

3) Availability concepts

    a) Developmental time schedule
    b) Delivery date of first items
    c) Delivery quantities
    d) Operational readiness

4) Reference list of supporting trade studies and DOD projects addressing the same or similar subjects.

5) Operational performance requirements

    a) Specific continuous control parameters
    b) Specific discrete peripheral functions
    c) Self-support
    d) Human interface

e) Hardware interface
f) Computer program effects
g) Failure-warning and required displays
h) Training
i) Weight and dimension limitations
j) Safety considerations
k) Reliability
l) Vulnerability/survivability
m) Security

The background and reasons for improved controller development have been covered already in the preceding documentation and the appendices.

Review of this background information gave rise to several areas of question. The first of these involved the effect of new controller development on controller standardization. Organizations such as the Aircrew Station Standardization Panel have expended considerable effort in attempts to standardize cockpit controller configurations. These efforts have been aimed at reducing the pilot adaptation required when transitioning from one vehicle type to another. The introduction of a new controller configuration represents, in effect, a de-standardization and therefore each new controller configuration developed must be evaluated from the standpoint of its effect on transition adaptation unless such controllers are intended for universal application. If universal application is the intent, then one must consider the cost of retraining to the new standard as well as any reduction in cost which may be achieved through the introduction of an improved controller configuration. Consequently, for each new flight control system and flight controller configuration being considered one must ask the question, "Is this new configuration operationally desirable, feasible, and what are its chances of acceptance?" This question cannot be answered until the flight control and controller concepts have been identified and trade studies can be conducted. In view of the background information pertinent to controller concepts, it was assumed for the purposes of this study that the introduction of advanced flight control concepts would necessitate and justify the development of an improved controller configuration. A secondary question hinges about a comparison of the advantages to be gained through improved displays as opposed to those to be gained from improved controls. As has already been stated, arguments pertinent to the importance of controller and display development are considered beyond the scope of the study. However, because a human operator is involved with both the controls and the displays it must be realized that the effectiveness of the control will be affected to some extent by the adequacy of the associated displays. Therefore, for the purposes of this study advanced display developments have been considered only in light of their effect on advanced controller operation.

In the absence of other guidance, the following ground rules and design goals were adopted as guidelines with respect to logistics and availability concepts. The advanced flight control concepts under consideration were intended for demonstration in a CH-47C aircraft. Therefore, the operational requirements for deployment, location, and dispersal of advanced flight controllers for this system must be compatible with the deployment, location and dispersal of the CH-47C itself. As an additional design goal, good engineering practices must be employed to assure that advanced controller configurations do not impose increased manpower, facilities and material requirements on the user in the areas of operations, maintenance and training.

In order to be compatible with the overall TAGS demonstration program, it was necessary that six flight safety qualified advanced controllers be available within 12 to 14 months after initiation of the TAGS demonstration program. In view of the fact that qualified vendors estimated 16 to 24 months for delivery of the first qualified unit, the time schedule for advanced controller development became an unrealistic goal. The only way in which the schedule could be met was to conduct a preliminary search of existing technology in hope that among the printed records of controller experimentation some documentation could be found which would obviate the need for or reduce the magnitude of a full-blown controller development program. Initial search of patents and technical literature disclosed little evidence of any work ever having been done on controllers having more than three axes. However, the results of the search did indicate that patents on existing controllers offered many mechanization techniques which might be applicable to controller development. To date, 246 patents have been identified which are related to flight controllers. These cover the period 1895 through 1967 and include British, German and French as well as United States patents. Of the 246 patents reviewed, 133 show mechanizations directly applicable to controller development. The remaining ones are associated with automatic flight control systems and autopilots without regard for the type of control used. A tabulation of the patents reviewed is presented in Table II. In the table, those patents which are marked with asterisks contain basic claims which have been cited in references of other patents. By far, the most frequently cited patent is Patent No. 2,144,616 issued to Mr. Bert G. Carlson for a remote control means for airplane automatic pilot. This patent, issued in 1939, was assigned to the Sperry Corporation. Mr. Carlson is well known for his work in autopilot controls and side arm controllers. Equally well known, is Mr. F. H. S. Rossire of The Bendix Corporation. Mr. Rossire's work also has primarily been directed toward the development of automatic pilots and automatic pilot controls. It is interesting to note that one or more patents have been issued for controller developments almost every year since 1922. Heavy concentrations during the periods 1945 through 1947 and 1949 through

51 perhaps are indicative of the requirements for improved controllers which developed during World War II and the Korean conflict. As might be expected, most of the patents listed in the Table were classified under Class 244 Aeronautics-Aircraft Control. In fact, this state-of-the-art patent search included the entire classes 244-77 Electric Automatic Aircraft Control, and 244-83 Pilot Operated Aircraft Control. In considering the development of multiple axis controllers, one also should not overlook Class 74, Machine Elements and Mechanisms and specifically Class 74-471, Multiple Controlled Elements. The assignees listed in the Table are those which existed at the time of patent issue. No attempts were made to determine patent assignments subsequent to patent issue. A review of the assignments listed confirms that those companies contacted pertinent to advanced controller development are probably the most active in the field. These companies were listed in Table I. From the patents issued to date, it appears that two and three axis concepts are more popular subject matter with the inventors than are one and four axis concepts. It is not known at this point if this is because no one has been able to conceive an effective four axis mechanization scheme or if the inability of operators to control four axes simultaneously with a single device has made the successful pursuit of such development technologically improbable. Certainly, one of the studies conducted early in any advanced development program for aircraft controls should be directed at determining which of the following control configurations a pilot can manipulate most easily.

(1) Two axis with the right hand, one axis with the left hand, and one axis with the feet.

(2) Two axis with the right hand, and two axis with the left hand.

(3) Three axis with the right hand and one axis with the feet.

(4) Three axis with the right hand and one axis with the left hand.

(5) Four axis with the right hand.

It appears that the most popular operational concepts involve providing for brakes and directional control with conventional foot pedals, while providing for the remaining axes with either center or side stick controls or the conventional column and yoke. It is easy to conceive how the column and yoke concept might be preferred, since this configuration most nearly resembles an automobile control system, with which most pilots are familiar prior to their flying training. This concept probably represents the minimum in adaptive processes when transitioning from an untrained civilian

PATENT NUMBER	INVENTOR	DATE	CLASS	SUBJECT	ASSIGNED TO	REMARKS
3,331,972	W. Moller	2/18/67	310-10	Magnetic Control Stick System	Bodenseewerk Perkin - Elmer	2 Axis, Side-Stick - Hall Effect
3,271,532	A. E. Lopez	9/6/66	200-6	3 Axis Finger Tip Controller	USA-NASA	3 Axis, Finger Switch - Bang Bang
3,270,260	M. H. Mehr	8/30/66	317-255	Stick-Operated Diaphragm Control	Measurement Systems Inc.	2 Axis, Side-Arm - Capacitance
3,260-826	R. M. Johnson	7/12/66	200-157	3 Axis & Translational Controller	Ling-Temco-Vought Inc.	3 Axis Rotational, 2 Axis Trans. Pot.
3,219,296	R. F. Rasmussen	11/23/65	244-83	Manual Control Apparatus	Honeywell, Inc.	2 Axis, Side Stick, Potentiometer
3,209,612	E. Tonnies	10/5/65	74-471	Control Assembly	Hamburger Flugzeugbau	2 Axis, Yoke, Mechanical
3,149,806	M. F. DeBoy	9/22/64	244-83	Side Arm Controller	USA-USN	3 Axis Electro-Magnetic
3,106,371	R. S. Brannin	10/8/63	244-83	Myoelectric Control System	Sperry Rand Corp.	3 Axis Myoelectric
3,028,126	E. C. Holleman	4/3/62	244-83	3 Axis Controller	USA-NASA	3 Axis Potentiometer
3,022,850	J. B. Bidwell	2/27/62	180-77	Single Stick Controller	General Motors Corp.	2 Axis, Side Arm, Potentiometer
3,017,142	F. H. S. Rossire	1/16/62	244-77	Manual Controller	The Bendix Corp.	2 Axis, Side Arm, Synchromotor
3,011,739	W. C. Boyce	12/5/61	244-83	3 Axis Side Controller	Ling-Temco-Vought Inc.	3 Axis, Side Arm, Potentiometer
3,991,963	C. G. Peterson	7/11/61	244-83	Aircraft Control Column	Vard, Inc.	2 Axis, Yoke, Mechanical
2,986,361	G. E. Codding	5/30/61	244-140	Aircraft Cockpit Arrangement		2 Axis Side Arm, 2 Axis Pedals, Pot.
2,945,648*	K. A. Oplinger	7/19/60	244-77	Control Arrangements For Aircraft	Westinghouse Electric Corp.	3 Axis, Side Arm, Potentiometer
GB-889,454	W. Fleck	2/14/60	40-1	Improved Control Means	Short Bros. & Harland	2 Axis, Pistol Grip, Electromagnetic
2,895,086	R. H. Pettit	7/14/59	317-99	Control Stick Transducer	Sperry Rand Corp.	2 Axis, Stick, Force, E-M
2,885,163	R. M. DeHaven	5/5/59	244-83	Aircraft Control Console	Hughes Aircraft Co.	2 Axis Rot., 2 Axis Trans., Yoke, Pot.
2,865,462	W. F. Milliken	12/23/58	180-79.2	Automotive Vehicle Control	General Motors Corp.	1 Axis, Yoke, Potentiometer
2,863,010	A. J. Riedl	12/2/58	200-5	Multiple Electric Switches		2 Axis, Side Arm, Bang-Bang
2,851,795	A. J. Sherman	9/16/58	35-12	Simulated Control Loading	Curtiss-Wright Corp.	2 Axis, Stick, Potentiometer
2,787,746	W. G. Redmond	4/2/57	318-19	Servo Control Hand Grip	Ling-Temco-Vought Inc.	2 Axis, Stick, Potentiometer
2,754,411	G. R. Dohrmann	7/10/56	240-61.9	Remote Control Spotlight	Otto Dohrmann	2 Axis, Side Arm, Bang-Bang
2,740,082	H. B. Sedgfield	3/27/56	318-489	Servo System	Sperry Gyroscope Co.	1 Axis, Potentiometer
2,681,777	F. H. S. Rossire	6/22/54	244-77	Automatic Steering System	The Bendix Corp.	3 Axis, Side Arm, Synchromotor
2,659,554	N. B. Murphy	11/17/53	244-77	Automatic Steering System	The Bendix Corp.	3 Axis, Side Arm, Potentiometer
2,659,275	V. E. Ericsson	11/17/53	89-41	Aiming Device For Guns	Aktiebolaget Bofors	2 Axis, Yoke, Synchromotor
2,618,447	J. A. M. LeCarme	11/18/52	244-83	Control Device For Aircraft	Societe Anonyme	2 Axis, Dual Side Arm, Mechanical
2,618,446	F. H. S. Rossire	11/18/52	244-77	Controller Unit	The Bendix Corp.	2 Axis, Pistol Grip, Synchromotor
2,614,776	F. H. S. Rossire	10/21/52	244-77	Autopilot Flight Controller	The Bendix Corp.	2 Axis, Side Arm, Synchromotor
2,610,520	B. H. Snow	9/16/52	74-471	Motion Translating Device	General Electric Co.	2 Axis, Side Arm, Synchromotor
GB-658,302	C. Bower	10/3/51	4-15	Control Mechanism For A/C	Reid & Sigrist, Ltd.	2 Axis T-Handle For Prone Position
2,559,298	F. A. Hayes	7/3/51	244-79	Automatic Pilot Control	Singer Manufacturing Co.	2 Axis, Side Arm, Potentiometer
2,553,280	F. H. S. Rossire	5/15/51	74-471	Stick Controller For Autopilots	The Bendix Corp.	2 Axis, Side Arm, Synchro
2,549,969	B. H. Hesemann	4/24/51	74-471	Manual Control Device		4 Axis, Stick, Mechanical

PATENT NUMBER	INVENTOR	DATE	CLASS	SUBJECT	ASSIGNED TO	REMARKS
2,543,450	L. W. Feagin	2/27/51	74-470	Control Stick		Trim Tab Push Button
2,539,753	C. G. Peterson	1/30/51	244-83	Aircraft Control Column	Tison Engineering Inc.	3 Axis-Yoke, 3 Intmt. Functions, Mech.
2,523,262	H. H. Amtmann	9/26/50	244-83	Three Dimensional A/C Control		3 Axis, Side Arm, Mechanical
2,521,680	H. H. Amtmann	9/12/50	244-83	Aircraft Prone Position Control Sys.		3 Axis, Prone Position, Mechanical
2,516,796*	P. A. Noxon	7/25/50	244-77	Automatic Pilot	The Bendix Corp.	3 Axis, Side Arm, Synchro
2,516,641*	N. B. Murphy	7/25/50	244-77	Automatic Pilot Control	The Bendix Corp.	3 Axis, Side Arm, Synchro
2,507,016	F. H. Hesh	5/9/50	200-6	Multiple Pole Switch		2 Axis, Side Arm, Bang-Bang
2,481,776	A. S. Osborn	9/13/49	201-48	Rheostat Control Device	Honeywell, Inc.	2 Axis, Side Arm, Potentiometer
2,471,821	R. J. Kutzler	5/31/49	244-77	Aircraft Control Apparatus	Honeywell, Inc.	3 Axis, Side Arm, Potentiometer
2,470,968*	L. E. Aske	5/24/49	201-48	Rheostat Control Device	Honeywell, Inc.	3 Axis Side Arm, Potentiometer
2,464,629	C. M. Young	3/15/49	244-77	Maneuvering Automatic Control	General Electric	2 Axis Side Arm, Bang-Bang
2,463,170	L. D. Grignon	3/1/49	171-119	Variable Inductance Device	Twentieth Century Fox	1 Axis, Hand Wheel, Electromagnetic
2,461,194	W. K. Beetle, Jr.	2/8/49	244-83	Control Unit For Airplanes	Dayton Aircraft Products	3 Axis, Yoke, Mechanical
2,457,884	R. E. Fulton, Jr.	1/4/49	244-2	Roadable Airplane	Continental, Inc.	2 Axis, Yoke, Mechanical
2,454,071	J. P. Lidral	11/16/48	137-144	Gun Control Mechanism	The Boeing Company	2 Axis, Yoke, Hydraulic
GB-596,881	P. A. M. Valroger	1/13/48		Devices For Piloting Aircraft		3 Axis, Yoke, Mechanical
2,431,290	R. Wilderman	11/18/47	74-471	Control Gearing & Lever		2 Axis, Side Arm, Mechanical
2,424,523	M. Watter	7/22/47	244-86	Aircraft Operating Mechanism	The Budd Company	Rudder Pedals & Brakes
2,417,725	D. R. Zuck	3/18/47	244-83	Flight & Ground Control		3 Axis, Yoke Plus Steering
2,411,770	C. H. Zimmerman	11/26/46	244-83	Prone Control Column	United Aircraft Corporation	3 Axis, Prone Column, Mechanical
2,407,322	D. K. Morrison	9/10/46	74-471	Differential Control Device		2 Axis, Yoke, Mechanical
GB-578,657	A. G. Rose	7/8/46		Improvement In Gun Mounting	Rose Brother, Ltd.	2 Axis, Over-Shoulder, Mechanical
GB-578,118	R. Ponting	6/17/46		Improvement In Gun Controls	Bristol Aeroplane Co.	2 Axis, Yoke-Potentiometer
2,397,978*	C. L. Paulus	4/9/46	200-6	Stick Control Unit		2 Axis, Side Arm, Bang-Bang
2,397,475	E. W. Dinga	4/2/46	250-2	Control Apparatus For Moving Vehicles	W. L. Maxson Corp.	2 Axis, Stick, Potentiometer
2,396,309	F. A. Wodal	3/12/46	244-83	Airplane Control		3 Axis, Yoke, Mechanical
2,393,892	C. DeGanahl	1/29/46	250-2	Remote Control System	Reconstruction Finance Corp.	2 Axis, Stick, Electromechanical
2,390,846	T. Obszarny	12/11/45	200-17	Hand Grip Control Switch	Guardian Electric	3 Independent Grip Switches
2,379,778	J. W. Allen	7/3/45	192-02	Fire Director	The Bendix Corporation	2 Axis, Stick, Potentiometer
2,373,065	V. E. Stevens	4/3/45	244-86	Aircraft Control Apparatus		Brake & Rudder Pedal, Mechanical
2,369,258	H. V. Shebat	2/13/45	244-122	Aircraft		2 Axis, Head Operated, Mechanical
2,355,026	O. C. Koppen	10/1/44	244-111	Airplane	General Aircraft	3 Axis, Yoke & Pedals, Mechanical
2,340,237	R. H. Upson	1/25/44	244-83	Airplane Control Mechanism	Consolidated Vultee	4 Axis, Yoke + Pedals + Lever, Mechanical
2,331,790	H. L. Nichols, Jr.	10/12/43	60-52	Hydraulic Control Valve		2 Axis, Sidearm, Fluidic

PATENT NUMBER	INVENTOR	DATE	CLASS	SUBJECT	ASSIGNED TO	REMARKS
2,284,611	G. E. Barnhart	5/26/42	89-41	Remote Control Gunmount		2 Axis, Handknob, Fluidic
2,277,883	F. E. Rich	3/31/42	201-55	Rheostat	Westinghouse	2 Axis, Handknob, Rheostat
2,257,852	J. Nicol	10/7/41	74-472	Combination Control	Divco-Twin Truck Co.	2 Axis, Side Arm, Mechanical
2,221,462	A. A. Trambly	11/12/40	277-69	Hydraulic Control Valve		3 Position, Bang-Bang, Fluidic
2,219,601	O. F. Quartullo	10/29/40	180-77	Automotive Vehicle Control	White Motor Co.	2 Axis, Yoke, Mechanical
F-857,592	Curtiss-Wright	9/19/40		Airplane Command System	Curtiss-Wright	1 Axis, Circum. Yoke, Mechanical
2,203,671	B. G. Carlson	6/11/40	244-76	Airplane Automatic Pilot	Sperry	3 Axis, Sidearm, Pneumatic
F-853,109	R. Vogt	3/11/40		Stabilization Mechanism	Blohm & Voss	2 Axis, Side Arm, Mechanical
2,173,538	J. D. McKellar	9/19/39	244-75	Airplane Control System		3 Axis, Yoke + Pedals, Mechanical
2,172,813	W. D. Waterman	9/12/39	244-83	Airplane Control		3 Axis, Yoke, Mechanical
2,162,862	A. Protzen	6/20/39	244-77	Attitude Control Means	Siemens Apparate	3 Axis, Electrical, Potentiometer
2,156,288	T. B. Holliday	5/21/39	244-50	Flying Automobile		3 Axis, Yoke, Mechanical
2,144,616*	B. G. Carlson	7/24/39	244-79	Autopilot Remote Control	Sperry	3 Axis, Side Arm, Pneumatic
2,134,509	F. C. Frank	10/25/38	244-86	Brakes	The Bendix Corp.	1 Axis, Toe Pedals, Mechanical
2,122,306	R. F. Volz	6/28/38	74-10	Radio Control Device	N. V. Phillips	2 Axis, Side Arm, Mechanical
2,110,989	R. E. Rickson	3/15/38	74-489	Handlebar Control Device	E. F. & R. G. Jago	1 Axis, Handlebars, Mechanical
2,110,516	F. E. Weick	3/8/38	244-75	Airplane	Fred E. Weick Associates	3 Axis, Yoke
2,082,410	E. G. McCauley	6/1/37	137-144	Fluid Pressure Controller		2 Axis, Sidearm, Fluidic
2,066,375	F. M. Truman	1/5/37	244-83	Aircraft and Control		3 Axis, Yoke, Mechanical
2,057,088	F. O. DeMillar	10/13/36	121-46.5	Fluid Pressure Controller	Gallon Iron Works	1 Axis, Side Arm, Fluidic
F-797,477	A. Darnet & R. Stock	10/4/36	GR6-CL4	Airplane Controller		3 Axis, Yoke & Pedals, Mechanical
2,005,061	F. W. Thomas	6/18/35	244-29	Airplane Control		3 Axis, Yoke & Pedals, Mechanical
1,987,733	P. H. Dusummier	1/15/35	88-40	Control Device		3 Axis, Side Arm, Potentiometer
1,987,066	E. G. Kingston	1/8/35	74-530	Vernier Adjusting Control	General Aviation	1 Axis, Side Arm, Mechanical
1,973,453	D. F. Whiting	9/11/34	179-171	Multiple Gain Control	Movietone News Inc.	Triple-Ganged Potentiometers
1,954,272	E. C. Taylor	4/10/34	200-6	Signal Switch		2 Axis, Side Arm, Bang-Bang
1,923,290	G. A. Wood	8/22/33	244-29	Airplane Control		2 Axis, Stick, Mechanical
1,911,444	C. D. Fator	5/30/33		Contact Gripping Device	USA-USA	Single Switch For Stick
1,909,182	W. M. Lanagan	5/16/33		Hand Lever		1 Axis, Side Arm, Mechanical
1,900,068	R. P. Mueller	3/7/33		Aircraft Control Mechanism		3 Axis, Yoke, Mechanical
1,880,138	F. Hubl	9/27/32		Mechanical Work Device		1 Axis, Side Arm, Bang-Bang
G553,559		6/27/32	35B-7	Mechanical Control Stick		2 Axis, Stick, Mechanical
1,864,329	C. Volk	6/21/32		Control Mechanism		3 Axis, T-Handle, Mechanical
1,855,988	J. Ranasey	4/26/32		Flying Control For Airplanes		3 Axis, Yoke, Mechanical

PATENT NUMBER	INVENTOR	DATE	CLASS	SUBJECT	ASSIGNED TO	REMARKS
1,829,037	B. L. Bobroff	10/27/31		Switch For Signaling		2 Axis, Finger Tip Bang-Bang
1,820,906	C. R. Bowers	9/1/31		Control Device For Airplanes	Charles T. Stedman (Pers)	2 Axis, Yoke, Mechanical
1,810,159	J. E. Carol	6/16/31		Automatic Propeller Control	Hammons & Jones (pers)	1 Axis, Push Button
1,807,848	K. Kollinek	6/2/31		Brake and Steering Device	Knorr-Bremse	2 Axis, T-Handle, Fluidic + Mech.
1,747,344	H. S. Bell	2/18/30		Airplane Steering Mechanism		3 Axis, Yoke + Stick + Pedals, Mech.
1,747,251	J. D. Langdon	2/18/30		Steering Gear For Airships		2 Axis, Yoke, Mechanical
1,714,170	D. K. Jette	5/21/29		Flying Machine		2 Axis, Yoke, Mechanical
1,694,477	G. W. H. Long	12/11/28		Dirigible Control Mechanism		2 Axis, + Wheel, Mechanical
1,686,850	R. French	10/9/28		Traffic Signal		2 Axis, Side Arm, Bang-Bang
1,666,761	W. Wait, Jr.	4/17/28		Seat & Control Mechanism	Curtiss Aeroplane Co.	2 Axis, Seat, Mechanical
GB-271,460						
F-620,519						
1,605,398	C. R. Fairey	11/2/26		Controlling Device For Airplanes		4 Axis, Double Wheel, Mechanical
1,591,433	P. C. Pommer	7/6/26		Handpiece For Gear Levers		Human Factors Only
1,553,262	J. Perna, Jr.	9/8/25		Rheostat Switch		1 Axis, Hand Knob
1,550,416	W. H. Barling	8/18/25		Control Device		2 Axis, Side Arm, Mechanical
1,536,515	N. E. Methlin	5/5/25		Control Post	Schneider & Co.	2 Axis, Yoke & Wheel, Mechanical
1,529,254	J. Humbrecht	3/10/25		Periscope	Optische Anstalt C.R. Goerz	2 Axis, Side Arm, Mechanical
1,508,591	L. Breguet	9/16/24		Means For Controlling Airplanes	Societe Anonyme	2 Axis, Yoke, Mechanical
1,462,531	M. C. Baumann	7/24/23		Rudder Control	Dayton-Wright Co.	1 Axis, Pedals, Mechanical
1,427,684	A. Grieves	8/29/22		Lever	International Harvester	1 Axis, Stick-Locking, Mechanical
1,426,193	J. E. Holmgren	8/15/22		Direction Indicator Switch		2 Axis, Fingertip, Bang-Bang
1,418,335*	E. A. Sperry	6/6/22		Automatic Pilot		2 Axis, Center Stick, Mechanical
1,415,176	J. T. Hughes	5/9/22		Airplane Control		3 Axis, Column, Mechanical
1,297,999	C. W. Bryant	3/25/19		Brake and Clutch Controller		2 Axis, Side Arm, Fluidic
1,285,814	J. A. Silsbee	11/26/18		Universal Motion Operating Device		2 Axis, Side Arm, Fluidic
1,257,141	W. F. Snowdon	2/19/18		Headlamp Controller		2 Axis, Side Arm, Bang-Bang
1,239,837	L. B. Sperry	9/11/17		Universal Control Handle	Sperry Corp.	2 Axis, Side Arm, Mechanical
1,085,575	G. H. Curtiss	6/27/14		Controlling Mechanism		2 Axis, Yoke & Wheel, Mechanical
1,061,917	S. N. Malterner	5/13/13		Aeroplane		3 Single Axis, Mechanical
1,061,701	P. Stumpf	5/13/13		Control Device	General Electric	2 Axis, Yoke & Wheel, Mechanical
1,025,482	B. Reid	5/7/12		Flying Machine		2 Axis, Yoke & Wheel, Mechanical
640,688	J. H. McCurty	1/2/00		Speed Governor	T. McEwan, Jr.	1 Axis, Column, Bang-Bang
539,863*	E. F. G. H. Faure	5/28/29		Searchlight Controller	General Electric	2 Axis, Side Arm, Potentiometer

*NOTE: Indicates Basic Patent Claims Frequently Cited In Other Patent References.

with automobile driver experience to a trained military pilot. However, because of the advantages offered by side stick controls in the areas of improved ingress and egress, increased instrument panel visibility, and decreased cockpit lethalization, the side stick concept has been achieving increased popularity both in the aircraft and the automotive industries. The diminutive size of most side stick controllers and the advantages mentioned previously, have made the side stick concept particularly amenable to space vehicle application, where capsule size precludes the use of control columns even if they were desirable from the human engineering standpoint.

2.4 Air Force Flight Dynamics Laboratory Concepts

Another potential study area should include efforts directed at determining operators preference between side stick and control yoke concepts for any advanced vehicle control system under development. Such a study was conducted to determine the best primary controller designs for jet transports by Hughes Aircraft Company, under contract from the Air Force Flight Dynamics Laboratory, Air Force Systems Command (Reference 19). The report on this study concluded, in general, that it seems extremely unlikely that any really radical departures from the current controllers will be tolerated by the pilot population until attitudes can be changed on reliability of fly-by-wire systems, the feasibility of effective primary control, and the possibility of utilizing alternate kinds of control feel feedback information. It is pointed out further, that the results of the present study do not point to any single best design. They do indicate that among the alternatives considered the dual side arm and the yoke and circumferential drive should be refined and tested further. Study results indicated that these innovations would be regarded as improvements over the current designs and that the degree of acceptance for these designs seems high enough to warrant their further development. In conjunction with these results, a mechanical, 2-axis dual sidearm controller has been developed by Hughes for the Air Force Flight Dynamics Laboratory. These controllers are presently undergoing installation and checkout in Cornell Aeronautical Laboratories' Variable Stability A-26 aircraft, with flight test scheduled to begin in mid 1969.

However, before accepting the above approach as a standard for all future flight control development, one should consider the subtle differences which exist between the agility of a jet transport and a highly maneuverable attack fighter aircraft or a combat helicopter. The effectiveness of proposed controllers must be a part of the feasibility and design trade studies for each proposed new vehicular control system. The Air Force constructed such a design comparison matrix as part of the jet transport controller study. This matrix is shown in Table III for illustrative purposes.

5 Research of Technical Literature

Research of technical literature to date has identified 450 documents pertinent to controllers and manual tracking tasks covering the period 1870 through 1967. The voluminosity of the material precluded reading all of this material, but casual scanning of the available abstracts indicated that about 90% of the material was directly related to control task analysis and the remaining 10% covered the relationship of control cueing and pilot control reaction. A bibliography of these documents is given in Appendix III. Additional works may be found in the Human Engineering Bibliographies published by Tufts University under the auspices of the Office of Naval Research. The technical documents listed in Appendix III represent the efforts of over 500 authors. While most of the articles represent single individual inputs, there are several authors whose contributions in both quantity and quality have qualified them as experts in their respective fields. Any developmental program embracing the field of man/machine interface and flight control systems certainly should include as part of its efforts a survey of published literature by the following authors:

Norman K. Walker, Norman K. Walker Associates, Bethesda, Maryland, on Human Operators In Closed Loop Systems

John W. Senders, Lecturer and Senior Research Associate, Psychology Department, Brandeis University, South Street, Waltham, Massachusetts on Human Operator Control Systems

J. I. Elkind, 50 Moulton St., Cambridge, Massachusetts, on Human Operator Control Systems

Harry P. Birmingham, Head, Engineering Psychology Branch, Applications Research Division, Naval Research Laboratories, Washington, D.C. on Manual Tracking Performance

W. L. Alford (deceased) Co-authors: W. K. Russell and S. A. Sjoberg, NASA Manned Space Center, Houston, Texas on Flight Investigation of Flying Qualities and Performance

CONTROLLER TYPE	SPRING GRADIENT	BREAKOUT FORCE	DAMPING	CENTER NEUTRAL ADJUSTMENT	MASS BALANCE	SENSORS	DEADBAND AT NEUTRAL	FLIGHT EXPERIENCE	SLAVING	PIVOT	GRIP	CONTROLLER MOTION PITCH, ROLL, YAW	CONTROLLER MOTION PITCH, ROLL
1. Hughes NASA...APOLLO Docking and Rendezvous	Fixed 0.5 lb deg- to soft stop at ±2 deg	Adjustable 0 to 2 lbs	No	No	No	Switches at ±5 deg and ±15 deg plus pots	Negligible	Simulator Evaluation	No	Pitch at wrist center, roll and yaw at grip base	Conventional hand	±15 deg	
2. Hughes, Tow Helicopter Studies	No	Negligible	Adjustable 0 to locked	No Center Return	No	Pots	Negligible	Airborne Evaluation	No	At grip base	Pencil		±30 deg
3. Hughes Link T27 Trainer Rendezvous Control (Translational Thrust Control)	Fixed	Negligible	No	No	No	Switches	±1/8 in.	Trainer Evaluation	No	At grip base	Palm	±1/8 Longitudinal ±1/8 Lateral Thumb switch Vertical	
4. Hughes Link T27 Trainer Rendezvous Control (Attitude Control)	Fixed Pitch 5 in lb Roll 3 in lb Yaw 9 in lb Torques	Negligible	No	No	No	Pots	Negligible	Simulator Evaluation	No	Approximately 6 in. from palm all axes	Special Hand grip	±30 deg Yaw Lockable via base switch	
5. Hughes Combined Three-Axis Hand Controller	Fixed Pitch 0.1 oz/deg Roll 0.33 oz/deg Yaw 0.36 oz/deg	Fixed Pitch 18 oz Roll 7 oz Yaw 16 oz	No	10 deg All Axes	No	Pots	Negligible	Simulator Evaluation	No	Wrist	Special Gimballed	Pitch ±30 deg Roll ±45 deg Yaw ±30 deg Roll lockout via thumb switch	
6. Hughes Single Axis Wheels	Fixed 0.13 oz/deg All Axes	Fixed 3.3 oz All Axes	No	No	No	Pots	Negligible	Simulator Evaluation	No	Finger Operated wheels and knob	Roll and pitch thumb-wheels yaw knob	±30 deg	
7. Hughes Three-Axis Hand Controller - NASA Operator Modes of Control	Fixed Pitch 3 oz/deg Roll 2 oz/deg Yaw 3 oz/deg	Adjustable 0 to: Pitch 10 oz Roll 14 oz Yaw 20 oz	No	±10 deg All Axes	No	Pots and Switches at ±6 deg	Negligible	Simulator Evaluation	No	At grip base approximately 6 in. from pivot to wrist	Conventional Hand grip	±30 deg	
8. Martin/VST Side Stick	Adjustable 3 Springs 2 1/2 lbs/deg 4 lb/deg	Adjustable Torque from 1 in lb to 11 in lb	Adjust Damping Ratio 0.2 to 3.0	Pitch: 5 deg Aft, 17 deg Forward Roll: ±5 deg	Yes All Axes	Linear pots	Negligible	Under Development	No	At base of wrist	Conventional hand grip	±18 deg All Axes	
9. NASA AMES 3° Side-arm Controller Model IV				No	Yes	Strain Gauges		Unknown	No	At grip base	Conventional hand grip	±20 deg	
10. Two-Axis Miniature Controller Royal Aircraft Establishment Ministry of Aviation	Not Available Typical Forces: 4 lbs at 150 kt 1.7 lbs at 350 kt	0.5 to 1.0 lb	No	No	No (extremely low mass mechanism)	Linear pots (dual)	Negligible	AVRO 707C Test Vehicle (High g Maneuvers)	No	Wrist Center-line ahead of hand	Finger tip control		Very limited motion approximately ±1.2 in Roll and Pitch
11. Minneapolis-Honeywell X-15 Electric Side-Stick	Variable 0 to 1 lb deg	Variable 0 to 10 lb	Variable 6 in oz to locked	Pitch ±15 deg Roll ±25 deg	No	Pots and Strain gauges	Variable	Yes JF-101A	No	Pitch at wrist pivot, roll at heel of hand	X-15, with ballooned		Pitch ±25 deg Roll ± 35 deg
12. Sperry Phoenix Fly-by-Wire Sidestick Controller	Pitch: 0.7 lb deg to 10 deg, 1.5 lbs Deg 10 to 15 deg, Roll: 0.3 lbs/deg to 7 deg, 0.9 lb/deg 7 to 12 deg	0.75 lb	1/4 sec from first stop to neutral, no overshoot	15 deg forward 8 deg inboard	Mass unbalance 8 in oz at 3g (Maximum)	Synchros, Pots, or Strain gauges	Negligible	None	No	At grip base	Conventional hand grip		Pitch ±15 deg
13. Measurement Systems Model 438 Force Side Stick	N/A	N/A	N/A	N/A	N/A	Inductive reactance	N/A	Yes, Frankford Arsenal, HU-1B Helicopter	No	At grip base	Thick pencil		Rigid grip Force controller

TABLE III. AIR FORCE FLIGHT DYNAMICS LABORATORY SUMMARY OF STATE-OF-THE-ART IN SIDE ARM CONTROLLERS.

3. BASIC DESIGN CONSIDERATIONS

In addition to the information already presented, a review of available patent and technical literature results in an important conclusion. Considering all of the work which has been done over the past 100 years and considering how little change the results of these efforts have produced on controller configurations, it seems unlikely that The Boeing Company, Vertol Division will be able to make significant philosophical advances in controller development in the two to three years planned for the TAGS Demonstration Program. It appears that nothing short of a state-of-the-art breakthrough would significantly alter controller configurations and the only way Boeing/Vertol can achieve such a breakthrough is to devote considerable resources to a well defined program which is acutely directed at spear-heading the state-of-the-art in vehicular control.

In order to assess the magnitude of such a program and the resources required, it was necessary to identify and evaluate some of the specific problems which might be anticipated in a controller development program. Using the modified Englebart man/machine communications flow diagram of Figure 6 and previously defined operational requirements as a basis, the following functional requirements were established.

(1) Provided a device for translating physical force or motion into a proportional electrical signal.

   a) Analyze psycho motor forces/motions into appropriate components.

   b) Transduce components of psycho motor forces/motions into electrical signals.

   c) Check for validity of the input.

(2) Provide a means for processing electrical signals to effect proper interface with adjacent system elements.

From these word descriptions the functional flow diagram shown in Figure 7 was generated.

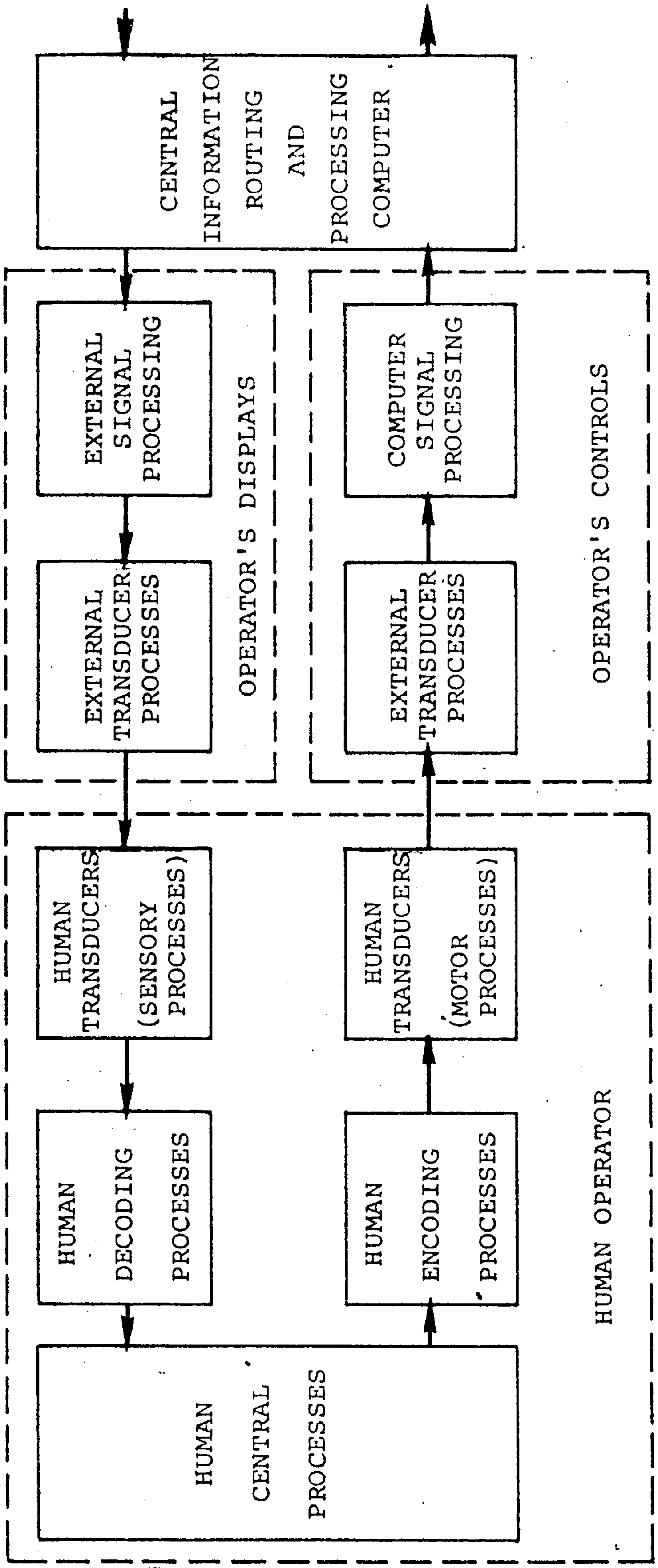


Figure 6. Modified Engelbart Man-Machine Communications Flow Diagram (Stanford Research Institute).

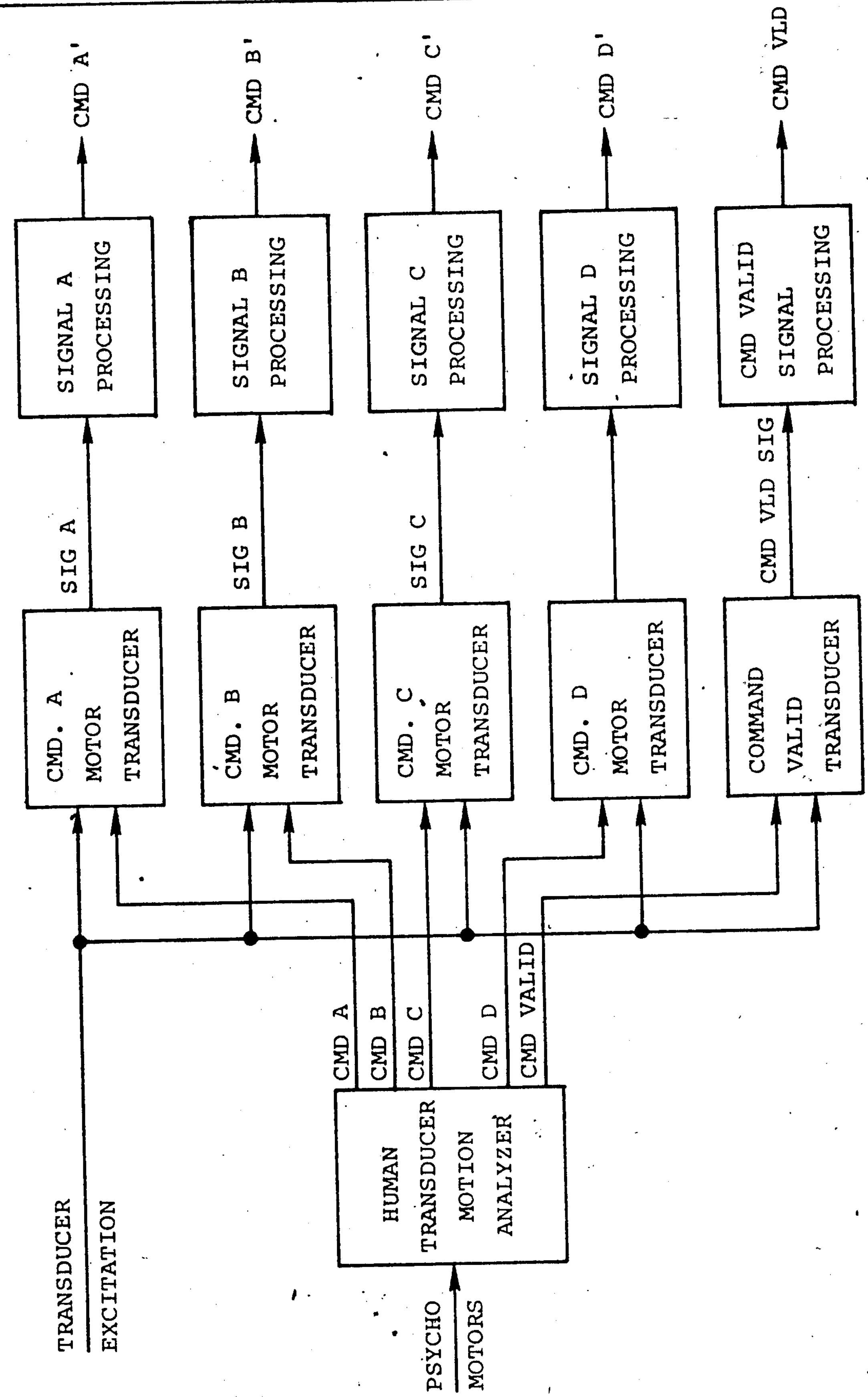


Figure 7. Controller Functional Flow Diagram.

PRELIMINARY FUNCTIONAL REQUIREMENTS ANALYSIS

In order to continue the functional analysis for the purpose of highlighting potential problem areas, it was necessary to present philosophical questions the answers to which would lead to the definition of design parameters and design criteria. The following paragraphs present these questions along with comments which represent preliminary thinking in pursuit of answers to these questions.

(1) What operational parameters are to be controlled?

MIL-STD-205 identifies most of the parameters which must be controlled in conventional power-attitude control systems in present helicopters (Reference 20). However, the introduction of advanced flight control concepts may require addition to, emphasis, deemphasis, or elimination of some of the existing control parameters. It is anticipated that at a minimum the following parameters will be required for primary control of most helicopters: sideslip angle, longitudinal velocity and position, lateral velocity and position, vertical velocity and position, engine torque, and rotor rpm. In aircraft having a weapon delivery mission which requires delivery of weapons from fixed mounts, it may also be necessary to directly control pitch, roll, and yaw angles. In order to preclude exceeding limitations on dynamic component loading, airframe stress and pilot comfort, it may also be necessary to limit if not control pitch, roll, and yaw rates as well as longitudinal, lateral and vertical accelerations. In many aircraft the following discrete and semi-discrete functions are incorporated as part of the primary controls: independent wheel brakes, intercommunication system on-off switches, radio transmitter on-off switches, searchlight filament on-off switches, landing-hover light on-off switches, force-feel trim controls, engine beep trim switches, torque balancing beep trim switches, aft wheel steering switches, searchlight controls, cargo release switches and weapon release switches. Initial considerations might include excluding from the primary controller those functions or parameters which (1) are not required on a continuous basis for parametric control and (2) can be handled better by the human operator if implemented by automatic or semi-automatic means. If a requirement exists to maintain conventional foot pedals to provide for independent wheel brakes, there seems to be little advantage in providing another separate device for direction control. One should also consider the question of whether directional control during taxi can best be handled by the same device used for directional control during flight or by a separate steering mechanism. Provisions for force-feel trim control can not be made until specific force-feel trim requirements have been

identified. Requirements for and implementation of rotor and engine rpm beep trim are dependent upon whether or not these rpm's are constant, discretely selectable or continuously variable over some predetermined range. If the speeds are variable one must consider in addition whether the speed control is to be manual, semi-automatic or fully automatic.

(2) What is the time sharing analysis for each of the parameters selected for control under question (1) above?

First a time line study must be conducted to see how much time is spent by the operator in performing each of his assigned functions. An analysis of this time line study will identify those functions which, if automated, would greatly contribute to unburdening the pilot. After these functions have been identified, one must next consider which of them are amenable for automation, and trade studies must be conducted to determine if automation would be cost effective.

(3) What physical appendages and/or psychomotors are available to command and control the operator functions identified under question (2) above?

Although research of past work done in the controller area did identify such exotic control systems as myoelectrics, neuroelectrics and voice control systems, it was decided for the purposes of this study that the control appendages would be limited to the head, the arms and the legs.

(a) What are the limits of psychomotive force, appendage motion and what are the associated response times for each of the human limbs?

The limits of appendage motion are well defined in existing human factor documents (References 21 through 26). It is suspected that there is a relation between psychomotive force, mass of the appendage and the response times which can be achieved with each of the appendages. Studies have been made of forces and motions which can be exerted by pilots in the control of a vehicle by NACA and should be available for reference.

(b) What are the psychological stresses on the pilot with cueing and without cueing?

If it can be shown that visual, aural or force-feel cueing is required to effect adequate control of the

parameters, then special studies will have to be initiated to define the type, accuracy and degree of quickening required for each type of cueing identified.

(c) What are the physiological stress and fatigue factors involved?

It is assumed that among these factors will be the number of control movements, the extent of control movements, and the force against which control movements must be made. In addition, one must consider the environmental factors such as temperature, humidity, vibration, noise, lighting and the combat situation, all of which have some effect on the psychophysical effectiveness with which the pilot performs his assigned control tasks.

(d) What levels of physical cross-coupling can be anticipated, particularly in the area of wrist articulation?

Perhaps the most significant single problem associated with a multiple axis side arm controller is centered around the fact that the human operator has difficulty controlling three or more parameters simultaneously with a single hand without introducing cross-coupling from one axis of control to another.

(e) What human vulnerability considerations should be included?

Most systems engineering analyses of modern day weapons systems include provisions for separated multiply redundant channels of information to reduce combat vulnerability. Certainly then the redundancy level of the human operators providing control inputs to these systems should be considered. As an example, one must consider if it is practical to provide a quadruply redundant flight control system which is operated by a single sidearm controller configured in such a manner that if the pilot's right hand is wounded the entire system is lost because he can not reach and operate the controller with the left hand.

(4) Which appendage should be assigned to each axis of command or control?

As has been stated, the ultimate system would allow for the maximum level of automated control which can be achieved without compromising any of the operator's command authority. Several factors influence the assignment of these appendages: one is the operator's confidence level. Certainly this will be a co-function with the psychophysical stress which is experienced by the pilot. In other words, that control device in which the operator has greatest prejudged confidence will probably be the one with which he can do the job best. A second consideration is the extent of the adaptive processes involved. In most cases, learning to fly an airplane involves learning to control an entire new family of devices. It might be worthwhile to consider such devices as automobile steering wheels, or bicycle handle bars for steering and foot accelerator pedals for longitudinal acceleration and velocity control in order to reduce these adaptive processes. The third factor is workload equalization, which is a cofunction with physiological stress and fatigue. There seems to be little advantage, for instance, in designing a controller which can be operated with a single hand if, in fact, such operation overtaxes the single hand and at the same time leaves the remaining hand and the feet without assigned tasks.

(5) What man/control coupling configuration is to be assigned to each axis of command and control?

Again there are several factors involved. The first is operator comfort. This factor will have to be rated in terms of the force, motion, stress, confidence, and workload levels previously discussed. The second factor again involves the extent of the adaptive processes required. As an extreme example, it might be entirely possible to design a controller which could be represented by a typewriter keyboard which is coupled to a digital computer for manual instructions. However, it seems ridiculous to design a flight control system which requires of the operator a degree of coordination similar to that of a typist or piano player, if a system could be designed which would permit the degree of coordination available in a truck or automotive driver to be put to use without additional training. The third factor involves physical cross-coupling between the man and the machine. Again, one of the problems in the past has been that a suitable single mechanization scheme has not been devised which is completely compatible with the mechanical articulation of all the human wrist and elbow joints.

(6) What are the operational performance characteristics?

Several operational features have been identified and merit discussion here.

(a) Zero-detent: It has been assumed that it would be desirable for the operator to be able to place the controller in a neutral or zero-detent position, without visual reference to the controller position. This requirement implies that either a mechanical detent must be provided or some alternative scheme must be provided for indicating the neutral position to the pilot. One alternative considered would be a force or displacement threshold or perhaps a combination of the two. If the force/motion threshold scheme is pursued questions arise as to whether this threshold should be optimized with respect to the 95 percentile pilot and fixed, or if it should be individually adjustable for each operator. If fixed, the breakout force or stiction must be defined, and if operator adjustable the range of breakout forces over which the controller adjustment will be operable must be defined. Additionally, questions regarding the quality and type of deadband sensitivity must be resolved. Past schemes have employed segmented or hat-shaped response curves in the area of the deadband. However, it is possible that a parabolic or cubic response curve may be more desirable. There have also been questions about electrical outputs at the mechanical null. Concepts which provide zero electrical output at the mechanical null often are plagued with sensitivity problems about the electrical null. It may be desirable to bias the electrical signal so that there is a finite voltage output for all positions of the controller.

(b) Postion-hold: A requirement has been generated that the controller employ some type of brake or clutch mechanism which will hold the commanded position of the controller even when the hand is removed. Such a mechanism should be sufficient to hold this position against inadvertent actuation of the controller by the operator. However, emergency breakaway forces must be considered in the event that the brake or clutch mechanism jams and can not be released. The controller should be no more difficult to operate in this case than is a conventional hydraulically boosted mechanical control system when the hydraulic boost fails. An additional question has been generated concerning the requirements for a two-speed or vernier control which will permit fine control around some nominal value during particular control tasks.

(c) Force-feel: The questions regarding the requirement for force-feel already have been discussed. If it is shown that force-feel cueing is required then one must ask if this is a gradient force-feel system or a fixed force system; and if gradient, should the gradient be operator adjustable, variable or programmed as a function of some coparameter such as velocity or acceleration. Again if fixed-force is considered, should it be optimized for the 95 percentile and fixed, or should it be operator adjustable? If variable or programmed force-feel is used, to what extent should the operator be able to control the constants of the force-feel programming? Also if programmed force-feel is used, should the programming be automatic by task (such as a loose control for taxi and a highly damped control for flying) or should it be self-adaptive control, which is highly expensive to implement? In all probability some form of controller damping will be required. Should this damping be dry, viscuous, inertial, electrical or mechanical? Also can a two-handed controller be devised whereby the human itself may provide a damping factor for the controller.

(d) Types of mechanization: From the outset force controls were deemed undesirable because it was shown in the early 1900s by Woodworth that the human operator is able to control motion or displacement with much greater ease and accuracy than he is force. Consequently a motion or displacement controller seems the most probable candidate for continuous control functions. However, discrete controls also must be considered for the semi-discrete or discrete functions which must be accomplished by the operator. In all probability, a combination of displacement and discrete controls would be used in an advanced controller concept.

(e) Loading and stress: Consideration of normal loading and stress is part of all good engineering design practice. In addition, ultimate stress loads for the vehicle in which the controller is employed must be considered. One must ask if the system must work if these ultimate stress loads are exceeded. In addition, for sidearm controllers, one must consider the type of stress loading that will result when a maintenance man kicks or stands on a controller to reach outside the aircraft to polish a windshield. The extent to which advanced controllers will be subjected to accidental damage must be considered.

(f) Environmental considerations: Perhaps the most important environmental consideration in helicopters is that of vibration. Both self-induced and pilot-induced oscillations must be considered. In the past it has been considered desirable from the human factors standpoint that the controller axes be oriented the same as the axes of control; that is, an operator pushes a throttle forward to cause an aircraft to go forward and pulls a thrust control lever up to get the aircraft to go up. Such orientation permit maximum coupling of the controller with the aircraft response in the axis involved. One possible means of reducing or circumventing these types of oscillations might be to locate the controller axis orthogonally to the axis of response. Other environmental factors for controllers include temperature, moisture, corrosion and dust. The range of each of these environmental factors to which the controller is to be exposed must be determined and the allowable sensitivity to these factors defined.

(g) Limits of control parameters: For each of the control parameters identified under question (1) above, the range of operation must be determined and the absolute limits established beyond which operation of the aircraft is unsafe.

(h) Limits of authority: Studies must be conducted which define exactly how much authority can be exercised by both the hardware system and by the pilot, and the question must be answered as to how much override capabilty must be provided for the pilot. It is assumed that in emergency situations the pilot will require authority over 100% of the normal range of the control parameter, and in addition may require the capability to exceed parametric limits at his discretion.

(i) Transfer functions: The gain, scaling and dynamic response of each control channel to operator inputs must be determined. In addition, for each flight control system under consideration, decisions must be made as to whether the transfer functions shall be part of the controller itself, part of the peripheral equipment to which the controller is attached, or if these functions shall be shared between the two.

(7) What mechanization embodiments are available for consideration?

Review of the patents previously identified suggest many possible mechanical coupling schemes. Some of the more common are shafts and levers (rotational, bending moment, and linear motion), pantographs, multiple-point parallel suspensions, gears (direct drive, rack and pinion, and bevel), belts and pulleys (toothed and untoothed), flexible cables, sprockets and chains, fluidics (hydraulic and pneumatic), and optical. Most of these mechanizations can be coupled to any of the following electrical transducers: digital (direct, absolute encoded and incrementally encoded), resistive (strain gage, potentiometer, and piezzo-resistive), inductive (LVDT, RVDT, synchro resolver and inductive potentiometer), capacitive (variable capacitor and demodulator), photoelectric, and Hall effect devices. Each mechanization scheme for coupling the mechanical control inputs to electrical transducers presents its own cross-coupling problems and must be trade-studied individually. Electrical input and output formats for the electrical transducers must be considered. AC, DC, pulse or digital forms are available and the amplitude, regulation, frequency, phase shift sensitivity, sampling rate, word length, and coding must be considered along with long and short term repeatibility, the minimum acceptable signal/noise ratio, and the response times. Consideration of output characteristics should include resolution, linearity and the capability for null offset. In order to clarify the null offset, suppose a pilot has commanded the neutral detent position with his controller and expected this command to produce some steady state condition in the flight control system, such as a hands-off hover in a helicopter. If the steady state is reached and the helicopter is in fact not hovering but is drifting, should some provision be made in the controller whereby the pilot can trim out the drift or offset the null.

(8) What signal processing is required?

The answer to this question depends primarily on the definition of the flight control system to which the controller will be coupled. In some flight control systems it may be possible to couple the controller directly to the dynamic system elements. In other systems, considerable mixing and shaping might be required before the signal is presented finally to the dynamic flight control elements.

(9) What other general considerations exist?

(a) Reliability: A numerical value for the flight safety reliability of an advanced controller will have to be determined. It does not seem unreasonable to require that failures shall not be more frequent than one per one hundred thousand flight hours (reliability = 0.999,99 for one hour flight). The reliabilities of individual elements comprising the advanced flight controller will have to be considered in order to determine the redundancy levels required to provide the overall reliability for the controller. In addition the redundancy configuration of the flight control system to which the controller will be coupled must be considered to assure that sufficient levels of redundancy are provided to make it compatible with the flight control system. Requirements for Built In Test Equipment (BITE) will have to be determined, particularly as applies to the monitoring of subsystem element performance, detection of element failure, switching to unfailed elements, advising the operator as to what portions of the controller have failed, and those BITE features required for pre- and post-flight operational and maintenance testing.

(b) Packaging Configuration

The total weight and volume of advanced flight controllers should be kept to the minimum practicable values. Individual dimensions which are not dictated by human factors considerations also should be kept to a minimum. The size and configuration of required electrical connectors will have to be considered as will the psychological appeal of the design. The fact that an advanced controller is designed for military application should not preclude consideration of color and other asthetic features in the design of the equipment, unless such considerations significantly reduce the cost effectiveness of the controller.

(c) Cost

An extrapolated curve of projected controller costs was presented in Figure 5.

(d) Producibility

The state of development and procurability of components used in developing advanced side arm controllers must be considered in light of their effects on the overall development and delivery schedule. Non-recurring engineering costs for production controllers is estimated to be in the vicinity of $100,000 and it is expected that a minimum development time of eight months will be involved after delivery of a detailed specification. Production rates probably will vary as a function of the quantity of controllers involved. An extrapolation of projected production rates is presented in Figure 8.

(e) Safety

In addition to the ingress and egress requirements already stated, the effect of inadvertent control, over-control and under-control must be considered in the development of advanced controller concepts.

(f) Vulnerability

Vulnerability of advanced controllers through accidental damage already has been mentioned. In addition, the vulnerability of advanced controllers through overt enemy action in combat must be considered.

(g) Maintainability

Many factors have been included here under the maintainability concepts. Among these are the adaptability of the advanced controller configurations to existing and projected flight control systems. Secondly, there is the interchangeability of advanced controllers between different flight control systems and between different aircraft employing the same control systems. Thirdly, comes replaceability, which is a measure of the time and effort required to replace an advanced controller in an aircraft in toto. Fourth, there is reparability which is the time and effort involved in repairing an item and consideration of the maintenance level at which the repair is performed. And lastly, there is the supplyability which is the logistics problem involved in supplying replacement advanced controllers to an operating unit. All of these "abilities" must be considered in the design of an advanced controller concept.

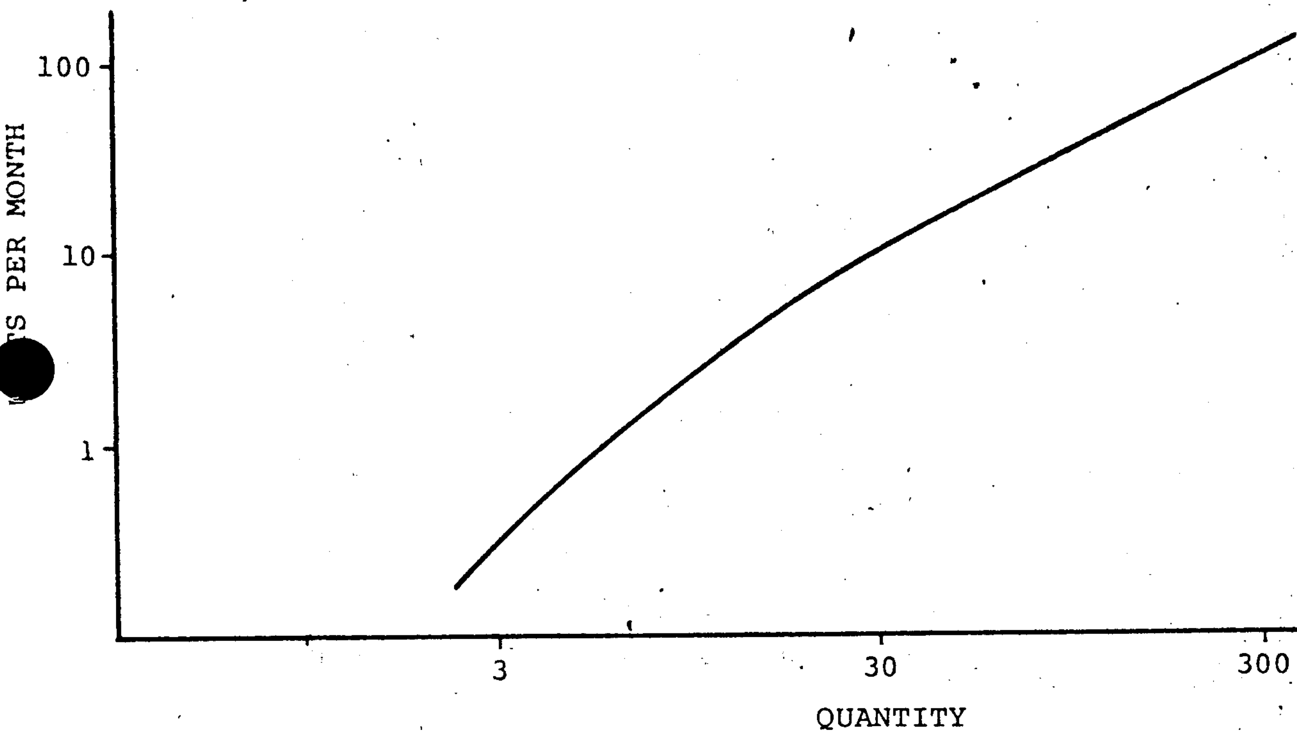


Figure 8. Possible Production Rate for Four-Axis Side-Arm Controller.

(h) Electromagnetic Compatibility and Radio Magnetic Interference

In electrical advanced controller concepts, consideration must be given to the susceptibility of the controllers to external and environmental electromagnetic disturbances as well as to the suppression of any tendency in the controller to generate electromagnetic disturbances.

(i) Interface Requirements

Tooling requirements associated with advanced controller concepts already have been discussed. In addition to the controller hardware itself, additional hardware considerations would include the hardware required for installation, checkout, maintenance, and training associated with the advanced controller. This would include consideration of both the tools and any additional ground support equipment required. If the advanced controller operates in conjunction with a central digital computer, one must also consider the application of software techniques to the calibration, phase shift compensation, transient compensation, reliability, and maintenance concepts of the advanced controller. If the introduction of advanced controller concepts affects maintenance and training facilities, the space and requirements for these facilities must be considered. In addition, the basic skills and additional training required for operational, maintenance and training personnel must be evaluated. Finally, the introduction of advanced controller concepts probably will require the generation of additional procedural information, including operational, maintenance, and training manuals.

(10) What additional problems are incurred with a dual installation?

Several questions have arisen concerning installation of two or more advanced controllers in the same aircraft. The first of these, and perhaps the most important, involves the question of remote following capability. In purely mechanical flight control systems it is conventional for the inactive controller to move to the same position occupied by the active controller, thereby eliminating any requirement for reorientation of the controls when transfer is negotiated from one pilot to another. In advanced flight control systems employing fly-by-wire techniques the implementation of such a remote following capability becomes more difficult

and indeed the requirement for such a capability should be re-evaluated. The second question centers about the characteristics of the controllers during the period of transferring authority from one pilot to another. Many operators feel that the activation of a transfer switch to effect transfer from one pilot to the other is improper, in that often emergency conditions do not afford sufficient time to activate such a switch. In cases where both operators are trying to operate the controls simultaneously, a question exists as to who is in command. In the case of mechanical control systems it is simply a case of the strongest man wins, however, the same is not true in fly-by-wire or electrical control systems. Therefore, a system of override or priority logic must be devised. Every possible technique must be evaluated and trade studied to minimize the transients which occur when transfer from one pilot to another is effected. Finally, changes in reliability requirements should be examined for the dual installation. It is possible that with two pilots and two controllers the reliability requirements per controller might be relaxed. However, if the controller is intended for universal application, it seems highly unlikely that controllers would be built with two different reliability design goals.

To date, only one of the foregoing questions has been treated in this division to any depth. An investigation of the characteristics of possible transducers for application to an advanced controller concept was conducted and reported (Reference 28). Historically, the most popular transducer scheme has involved the employment of precision potentiometers. However, the aforementioned study indicated that the most suitable devices from the standpoint of cost and reliability were synchros and resolvers. It was pointed out that both of these devices, however, do not lend themselves to compact multiple packaging. Direct digital encoding was considered too costly but a trade study was recommended to determine which was less costly, direct digital encoding or synchro resolvers plus the required analog to digital conversion, in the cases where a central digital computer was involved. It also was recommended in the study that solid state strain gages or piezoresistive devices be explored to see if the state-of-the-art would permit development without great expenditures in the areas of development and manufacturing.

5. CURRENT STATUS

One additional study was started in-house in the area of human factors. This effort involved preparation of proposed plans for pursuing tasks necessary during initiation of a controller development program. Using CH-47C functional flow diagrams, time line studies of pilot performance were initiated for the CH-47 in an attempt to define the LaPlace transforms for the pilot transfer functions. Additional efforts were aimed at identification of mechanical means for coupling pilot controller inputs to the flight control system and at defining evaluation criteria which would lead to selection of the best mechanical scheme for each axis of control. A matrix of control implementation devices and evaluation criteria is shown in **Figure 9**. Initial definitions of the evaluation criteria follow.

<u>Adaptability</u> - Requiring the minimum additional training or education above some pre-determined initial level in order to effect control.

<u>Naturalness</u> - Requiring the minimum conscious thought to effect proper control.

<u>Vulnerability</u> - Possessing the greatest capability for retention of control after the immobilization of one of the control appendages.

<u>Fatigue/Stress</u> - Requiring the least physical work and generating the least emotional pressure.

<u>Task Loading</u> - Providing the most even distribution of tasks among available appendages.

<u>Vibration</u> - The least subject to control error due to oscillation or G loading to which the pilot is subjected.

<u>Coordination</u> - Requiring the least degree of synchronization when performing two or more control tasks at once.

<u>Inadvertency</u> - Least subject to error during periods of inattention.

<u>Cross Coupling</u> - Most free from unintentional inputs associated with intentional inputs.

<u>Visibility</u> - Least likely to obstruct view.

<u>Accuracy</u> - Possessing greatest precision or ease of attainment of precision.

<u>Complexity</u> - Having the least number of motions required to effect control.

EVALUATION PARAMETER / CONTROL DEVICE	ADAPTABILITY	NATURALNESS OF RESPONSE	VULNERABILITY	FATIGUE/STRESS	TASK LOADING	VIBRATION, G-LOADING	COORDINATION REQUIREMENTS	INADVERTENT CROSS-COUPLING	COCKPIT VISIBILITY	TRACKING ACCURACY	OPERATIONAL COMPLEXITY	INGRESS-EGRESS CRASH SAFETY	
CENTER MTD. YOKE													
CENTER MTD. STICK													
VERTICAL SIDE-ARM GRIP													
HORIZONTAL SIDE-ARM GRIP													
FINGER KNOBS													
HELMET MOTION SENSOR													
STEERING WHEEL													
FINGER TOGGLE SWITCH													
HANDLE BARS													
MOVING ARMRESTS													
MODIFIED TRACK-BALL													
MYOELECTRIC													
PUSH BUTTON													
SLIDING SWITCH													
TOE PEDALS													
FOOT PEDALS													
PISTOL GRIP													
VOICE COMMAND													

Figure 9. Control Device Evaluation Matrix.

Safety - Presenting the least hazard or number of hazards to ingress, egress, and during crash.

In addition, existing human factors standards were used in an initial attempt to define angular motion limitations of the manual appendages. They are as follows.

1. Forearm - 81° in supination, 56° in pronation, oriented 12° off center.

2. Wrist - 73° in dorsiflexion, 72° in palmarflexion, oriented 0° off center.

3. Wrist - 13° in radial adduction, 36° in ulnar abduction, oriented 25° off center.

Unfortunately these efforts were terminated before completion because available resources were required for higher priority efforts.

Outside the company the only other active major efforts are those of the USAFFDL and USAAVLABS. The USAFFDL dual side arm controller demonstration program in the Cornell variable stability A-26 was discussed previously. The original 4-axis side arm controller developed by AVLABS has been assigned to CAE Industries in Montreal, Canada. It is the intent of CAE Industries to modify the mechanization for the purpose of improving the engineering. It is also CAE Industries' intent to take special precautions to insure that the original control philosophies represented by this controller configuration are preserved. In addition, AVLABS has negotiated a contract with the Norair Division of Northrop Corporation for the development and simulation of a six-axis side arm controller. This controller configuration was developed primarily as an investigative tool to assist in defining advanced controller operational requirements and characteristics. The development and simulation program is being monitored by flying and engineering personnel from both Boeing-Vertol and CAE Industries, as well as those from AVLABS. The writer had the opportunity to operate the Norair controller for a limited time in the Norair point-light source, 3-axis rotational, flight simulator. Experience was gained with the controller coupled to the simulator and coupled only to a recording oscillograph. The limited extent of exposure precludes very definitive comments. Generally speaking, inter-axis cross-coupling was experienced in most of the areas anticipated. While the Norair controller represents a very good first attempt at a multi-axis side-arm controller engineering model, I could find nothing to indicate sufficient inherent naturalness or simplicity to justify this controller as a candidate replacement for conventional helicopter controls. However, it must be realized that this model was in the embryonic stages and it is expected that continued exposure will result in improvement in this model.

CONCLUSIONS

Review of all the information presented previously gives rise to three major questions: 1) Is an advanced controller configuration operationally desirable; 2) If operational requirements for an advanced controller can be defined, can a configuration be conceived which will not only satisfy these requirements but also will be universal enough in its applicability to make it acceptable and salable to pilots, and 3) If a desirable and salable configuration can be designed, can it be mechanized? Other than general requirements for improved cockpit visibility, improved ingress and egress, and reduced cockpit lethalization, no definitive advanced controller requirements have been generated. Therefore, it seems reasonable to assume that the present controllers will be at least minimally satisfactory until such time as some new configuration is rated better by the operators by some individual standard of betterness. Subsequently, the major engineering management question arises as to whether industry should wait for the user to define new or additional operational requirements for improved controllers or undertake its own in-house funded research and development programs with the intent of conceiving a better controller configuration, building experimental models and exposing them to operator evaluation with the hope that they will be rated better than existing controls. In order to obtain guidance and subsequently to enable meaningful recommendations to management, the user market was surveyed in an attempt to determine just where within the man-machine interface areas a division such as Boeing-Vertol should be investing its available research funds. A significant clue was given by Colonels Watson and Dunham at the 1968 Forum of the AHS. In analyzing U.S. Army helicopter operations in Vietnam, man-machine interface problems were summarized best in the statement, "A great deal of work needs to be done in the area of cockpit comfort and location of equipment. As indicated by the suggestions, we still are experiencing far too many pilot squawks in the cockpit area and many of them have a safety connotation." These and other experienced helicopter pilots have made statements to the effect that, "We have the same damn problems now we had 20 years ago", and "we are still working with WW II cockpits". I think there is no question about whether or not cockpit improvements are needed. There are, however, questions as to what improvements are needed and who is to make them. Certainly the user should define the requirements and evaluate the end product to assure that the requirements have been satisfied. However, the user seldom has the engineering facilities to perform the analyses, simulation and construction of conceptual models required to produce the end product. Most prime aerospace system manufacturers depend highly on GFE in the cockpit area and consequently do not become involved in the production of component hardware. Component hardware manufacturers seldom possess the required knowledge of systems operations and total system details to produce a completely satisfactory end product without many design

iterations. Consequently, it appears to the writer that only the prime system manufacturer has the combined system knowledge of operation, engineering, manufacturing and evaluation required to understand all the implications and realize all the advantages associated with improved man-machine interface. In order to determine just what efforts promised most productive results, representatives of the Army's AVLABS, HumRRO, ECOM, CDC, USABAAR, APG; the NASA's Langley, ERC, NSC; the USAF's AFFDL; and the USN's NASC were interviewed pertinent to projected man-machine requirements. The following requirements were common to all organizations:

- o Increased IFR capability
- o Reduced training
- o Decreased pilot workload
- o Reduced probability of accidents
- o Increased standardization

When Boeing-Vertol's pilot population was questioned regarding how these goals might be attained, the following suggestions were offered by 19 pilots having a cumulative pilot experience of approximately 67,500 hours:

- o 45% - Improve instruments, indicators or displays
- o 27% - Improve cockpit integration through correlated controls and displays
- o 28% - Miscellaneous other cockpit improvements.

In response to specific questions pertinent to cockpit controls, the following suggestions were offered:

- o 52% - Leave primary flight controller configuration as is, but make other cockpit control improvements (e.g., force-feel, etc.)
- o 26% - Make no changes in present cockpit controls. They are satisfactory as they are.
- o 22% - Miscellaneous other controller configuration improvements.

RECOMMENDATIONS

The material presented herein and the experience gained during the assimilation of this material indicate that a major factor influencing recommendations for future activity is this division's commitment of research and development resources to the improvement of man-machine interface in future division products. Unless commitments are sufficient to produce significant results, the following recommendations are meaningless.

If, on the other hand, division engineering management commits significant research and development resources to the improvement of man-machine interface, the following recommendations are offered as guidance in the pursuit of such activities:

(1) Available IR&D resources should not be expended on the development of advanced controller concepts because:

(a) It is doubtful that the division can provide sufficient resources to achieve a technical breakthrough in universally applicable controllers within a meaningful time frame.

(b) The salability of a revolutionary advanced controller concept to experienced pilots is questionable.

(2) Available IR&D resources should be allocated as follows in pursuing improvement in man-machine interface:

(a) 45% to the research and development of advanced cockpit instruments and displays.

(b) 30% to the development of improved cockpit integration.

(c) 25% to the development of promising improvements to existing MIL-SPEC controllers and adaptation, if necessary, of such controllers to make them compatible with fly-by-wire systems.

(3) In keeping with objectives of paragraph (2c) above, customer funded R&D programs for controller development and improvement should be pursued for the purposes of:

(a) Improving customer relations, and

(b) Maintaining division technology in the area of cockpit controllers.

APPENDIX A

PRELIMINARY GENERAL DESCRIPTION OF A FOUR-AXIS SINGLE SIDE-ARM CONTROLLER

(Note: This is not a specification. It is a general description to be used for cost estimating purposes only.)

1. May sense either force or motion (motion preferred).

2. Will conform to general configuration shown in Figure 1.

3. Must contain four axes which develop independent electrical signals proportional to the force or motion applied to any axis, either individually or in combination, as follows:

   a. Rotation of the T-handle about its own lateral (y) axis produces an electrical output proportional to angular displacement (force). Limits of rotation - $\pm 40°$ from an x-y plane oriented 10° nose down (± 20 in-lb force)

   b. Rotation of the T-handle about its own vertical (z) axis produces an electrical output proportional to angular displacement (force). Limits of rotation - $\pm 30°$ from an x-z plane oriented 10° nose down left (± 15 in-lb force)

   c. Translation of the controller along the aircraft longitudinal (fore-and-aft) axis produces an electrical signal proportional to displacement (force). Limit of translation - $^{+8}_{-2}$ inches from neutral z-axis (± 20 lb force)

   d. Translation of the controller along the aircraft's lateral (side-to-side) axis produces an electrical output proportional to displacement (force). Limits of translation - ± 2 inches from neutral z-axis (± 20 lbs force).

4. Input power:

   Voltage - <u>one</u> of the following:

   *28VDC (*In the CH-47, DC Power is not as well regulated as AC Power)
   26 VAC, 400 hz, 1ϕ
   115 VAC, 400 hz, 1ϕ

   Current - 30ma/axis/channel maximum

5. Output signal formats - one of the following:

   DC Analog
   AC Analog
   Synchro
   Digital Serial

   Load Impedance - 1000 ohms/axis/channel minimum

6. Breakout forces - 1 in-lb in rotational axes
   1 lb in force or translational axes

7. Must have neutral detent which can be sensed through feel.

8. Ultimate load - 400 lbs in any direction distributed over 1 sq.in. area

9. Physical requirements:

   Weight - 18 lbs maximum

   Width - 5-3/4 inches (standard track width)

   Length - 12 inches maximum

   Depth - 9 inches maximum

10. Environmental Capability

    MIL-T-5422 (refer to Curve III for vibration)

    MIL-I-6181 for RFI

    Flight Safety Qualification Required - Full Production Qualification not Required.

11. Reliability - as a series element, it must provide sufficient redundancy to assure functional reliability of .999,999,999,846 for a 1-hour mission. It shall be at least triply redundant.

12. Must have capability to follow a remotely located controller operating in parallel.

13. Must have clutching mechanism which is thumb or heel-of-hand actuated to move controller. When disengaged, controller will have breakout forces greater than 25 in-lb in rotational axes and 30 lb in force or translational axes.

14. Will have the capability to produce synthetic feel proportional to force, acceleration (g), dynamic pressure (q), or other electrical analogs (only one analog will be used per channel for synthetic feel generation; however these quantities may

be mixed in the central computer and a single drive signal derived, if this is found to be desirable from the human factors standpoint).

Note: All forces and displacements are nominal in value and subject to change, dependent upon results of simulation and flight tests.

Alternate Controller

As an alternate, consider a controller which meets all of the above requirements, except for paragraph 3, which may be replaced with paragraph 3^1 which follows.

3^1 - Must contain three axes which develop independent electrical signals proportional to the force or motion applied to any axis, either individually or in combination as follows:

a. Same as 3a above.

b. Rotation of the T-handle about its own longitudinal (x) axis produces an electrical output proportional to angular displacement (force). Limit of rotation - $\pm 30°$ from an x-y plane oriented 30° up on the left (thumb) side.

c. Same as 3c above.

d. Not applicable.

In addition, paragraph 13 does not apply.

APPENDIX B

PROPOSED DEVELOPMENT FOR A TAGS CONTROLLER

One of the major areas of emphasis in this program will be the development of a simple and effective pilot's controller. Initial investigation of pilot's controller concepts at Boeing-Vertol has shown that side-arm controller concepts not only are technically feasible but also have a high probability of pilot acceptance. During the TAGS program, controller concepts will be reviewed and evaluated, with particular attention directed toward development of triply-redundant, side-arm controllers, such as the single four-axis model, shown in Figure B-1. Operational objectives will be considered carefully in establishing controller design criteria. The psychological stresses associated with maneuvers requiring adherence to precise flight profiles, such as instrument approaches and accelerated transitions in restricted corridors of high density traffic, should be reduced. Flight conditions such as steep approaches during near-zero visibility and flight during unstable atmospheric conditions require continuous manual control which produces physical fatigue. Proper pilot's controller design can minimize this type of fatigue. Also, pilot's confidence can be promoted through the development of control-force feel to effect optimal compatibility between the pilot and the flight control system.

Additional objectives are:

(a) Development of a capability for retention of any selected steady-state flight condition with a minimum of input control effort.

(b) Equalized distribution of pilot control loads over the operational flight spectrum.

(c) Provision for sufficient control restriction to preclude inadvertent over-control, while at the same time providing sufficient control slippage to allow pilot override should such action be necessary.

(d) Provision for sufficient logic to preclude confusion between pilot's and copilot's command inputs, particularly during periods of control transfer from one pilot to the other.

(e) Minimization of the pilot's adaptive processes involved in transitioning from vehicular controllers with which he is familiar to advanced flight controllers.

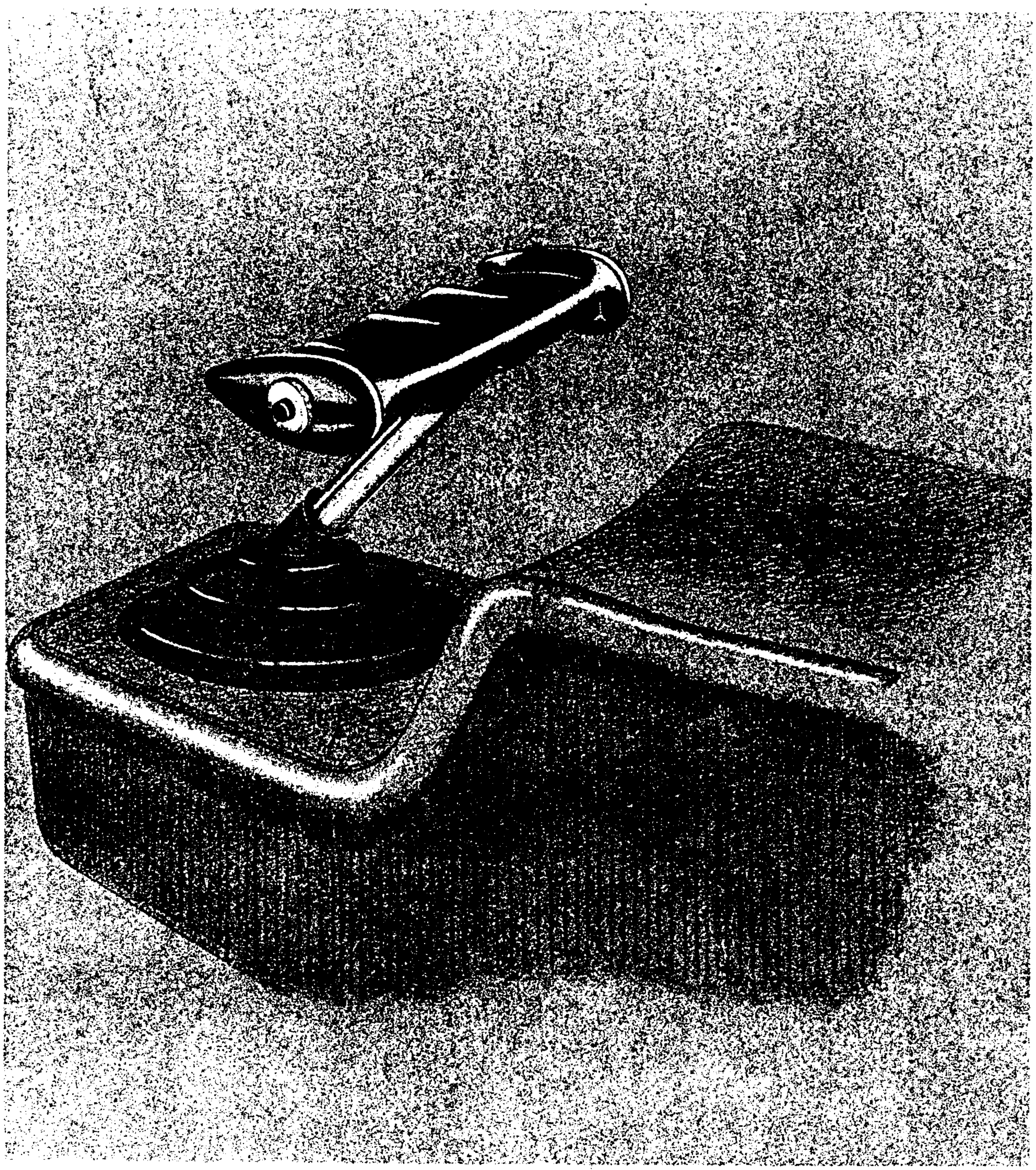


Figure B1. Vertol Artist's Concept of Side-Arm Control.

The development of a satisfactory controller will depend highly upon solution of anticipated problems in the areas of inter-axis crosstalk, mechanical suspension, limitations in physical flexure, mounting restrictions, and force loading. Boeing-Vertol proposes to consider several alternative control methods before final selection of the controller configuration. Investigations will include comparison of four-axis single side-arm, three-and-one-axis dual side-arm, and two-axis dual side-arm controllers as well as other force, rotational and linear translational control devices.

Based on results of laboratory and flight simulator evaluation of the three experimental models of different controller configurations, one configuration will be selected as most satisfactory for further refinement, development and incorporation into TAGS.

The controller will be designed to produce independent electrical signals proportional to the control action applied to its axes, either individually or in combination. It is anticipated that the signal outputs will be derived from linear resistive and/or inductive devices within the controller.

APPENDIX C

A BIBLIOGRAPHY OF AVAILABLE TECHNICAL LITERATURE PERTINENT TO CONTROLLERS AND CONTROL/ TRACKING TASKS

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